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SUMMARY

As a result of the vehicle oscillations occurring on free-flight number 5 of the approach and landing tests, an experimental study using a six-degree-of-freedom motion-base simulator has been made to determine the effect of control-system time delays on the occurrence of pilot induced oscillations (PIO's) on the vehicle handling qualities and on pilot tracking performance for a landing-approach configuration of the Space-Shuttle orbiter. A linearized math model was employed which represented a 300-knot orbiter with almost all time delays removed. Additional time delays were then inserted following the pilot's hand-controller signals. Only pitch and roll commands were used for vehicle control. The simulation employed an air-to-air tracking task as a means of emphasizing PIO tendencies. Two astronauts, two research pilots, and one simulation engineer served as test subjects. Results showed that PIO's occurred when the amount of added time delay approximated that existing for the orbiter configuration flown in the approach and landing tests (ALT). Increasing the amount of delay increased PIO occurrences and resulted in degraded tracking performance. Decreasing the amount of time delay eliminated the PIO's.

INTRODUCTION

During the Space-Shuttle-orbiter development program on free-flight landing number 5 of the approach and landing tests (ALT), the orbiter vehicle experienced pilot-induced oscillations (PIO's). Both pitch and roll PIO's occurred. No PIO's, however, were encountered on the first four ALT flights. Flight number 5, therefore, created a lot of interest because of the PIO's encountered. One factor contributing to this difficulty was believed to be the presence of time delays (transport lags) in the control system.

The present simulation study was undertaken to assess the effect of control-system time delays on the PIO tendency of an orbiter configuration. To minimize setup time, use was made of an existing simulation for studying the effect of time delays in simulators. (See refs. 1 to 4.) Accordingly, the simulation software was modified to incorporate a given orbiter configuration. The simulation employed an air-to-air tracking task rather than a landing task. Previous experience has shown that the use of such a tracking task is a good way for identifying PIO tendencies. In addition to PIO occurrences, an assessment was made of vehicle handling qualities (via Cooper-Harper ratings) and pilot tracking scores due to the presence of time delays.

Two astronauts, two research pilots, and one research engineer served as test subjects for the present study. For some of the tests an audio side task was employed to increase subject workload. Only the latter three subjects used the side task since the time available did not permit astronaut participation in these extra tests.

SYMBOLS

Numerical values are given for some quantities in both the International System of Units (SI) and in U.S. Customary Units for convenience. Measurements and calculations were made in U.S. Customary Units. The effective aerodynamic parameters used herein are referenced to a system of body axes with the origin at the vehicle center of gravity. (See fig. 1.)

a_X, a_Y, a_Z accelerations along the body axes caused by aerodynamic forces, m/sec^2

B audio-task tracking error (tone voltage), volts or Hz (scale factor is 460 Hz/volt)

b wing span, m

$\bar{c}$ wing mean aerodynamic chord, m

F statistical quantity associated with F distribution

F_{SX}, F_{SY}, F_{SZ} accelerations at centroid of motion base, m/sec^2

F_X, F_Y, F_Z aerodynamic forces along the body axes, N

g gravitational constant at sea level, $g = 9.8\ m/sec^2$

h altitude, m

I_X, I_Y, I_Z moments of inertia about the body axes, $kg\text{-}m^2$

I_{XZ} body-axis product of inertia, $kg\text{-}m^2$

K_* audio-side-task pilot gain

K_w thumb-wheel gain

K_{VCO} voltage-control oscillator gain

ℓ_j, m_j, n_j direction cosines ($j = 1, 2, 3$)

M_X, M_Y, M_Z aerodynamic rolling moment, pitching moment, and yawing moment about the body axes, N-m

m vehicle mass, kg

p, q, r rolling, pitching, and yawing angular rates about the body axes, rad/sec

$\bar{q}$ dynamic pressure, $\frac{1}{2}\rho V^2$, N/m^2

S	wing area, m^2
s	unbiased estimate of standard deviation
T_s	audio-task first-order divergence time constant, sec
t	statistical quantity of t-test of student's t distribution
u,v,w	vehicle velocities along the body axes, m/sec
V	total vehicle velocity, m/sec
V_x,V_y,V_z	components of vehicle velocity relative to flat-Earth inertial-coordinate axes, m/sec
W	vehicle weight, N
α	angle of attack, rad
α_t	trim angle of attack, rad
$\Delta\alpha$	angle of attack from trim, $\alpha - \alpha_t$, rad
β	sideslip angle, rad
δ_a	roll-control input after shaping, limiting, and scaling, rad
δ_{ac}	hand-controller deflection in roll, positive to right, deg
δ_e	pitch input after shaping, limiting, and scaling, rad
δ_{ec}	hand-controller deflection in pitch, positive rearward, deg
δ_s	audio-task thumb-wheel deflection, volts (scale factor is 0.4 rad/volt)
ε_h	horizontal (lateral) tracking error, m
ε_v	vertical tracking error, m
$\varepsilon_v + \varepsilon_h$	sum of vertical and horizontal tracking errors, m
η	elevation line-of-sight angle, rad
$\Delta\theta$	pitch altitude from trim value $(\theta - \theta_0)$, deg or rad
λ	audio-task instability setting, $1/T_s$, sec^{-1}
ξ	azimuth line-of-sight angle, rad
ρ	air density, kg/m^3

τ	added time delay in the roll- and pitch-control channels, units or msec (each unit equals 31.25 msec)
τ_p	added time delay in pitch-control channel, units or msec (each unit equals 31.25 msec)
τ_r	added time delay in roll-control channel, units or msec (each unit equals 31.25 msec)
ψ,θ,φ	Euler angles (yaw, pitch, and roll angles, respectively), deg or rad

Symbols for aerodynamic and control-system combination:

C_l	rolling-moment coefficient, $M_X/\bar{q}Sb$
C_m	pitching-moment coefficient, $M_Y/\bar{q}S\bar{c}$
C_n	yawing-moment coefficient, $M_Z/\bar{q}Sb$
C_X	axial-force coefficient, $F_X/\bar{q}S$
C_Y	side-force coefficient, $F_Y/\bar{q}S$
C_Z	normal-force coefficient, $F_Z/\bar{q}S$

$$C_{Z_\alpha} = \frac{\partial C_Z}{\partial \alpha} \qquad C_{Y_p} = \frac{\partial C_Y}{\partial \frac{pb}{2V}} \qquad C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$$

$$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha} \qquad C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta} \qquad C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$$

$$C_{X_\alpha} = \frac{\partial C_X}{\partial \alpha} \qquad C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}} \qquad C_{l_{\delta a}} = \frac{\partial C_l}{\partial \delta_a}$$

$$C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}} \qquad C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}} \qquad C_{n_{\delta a}} = \frac{\partial C_n}{\partial \delta_a}$$

$$C_{m_{\delta e}} = \frac{\partial C_m}{\partial \delta_e} \qquad C_{Z_q} = \frac{\partial C_Z}{\partial \frac{q\bar{c}}{2V}} \qquad C_{Y_{\delta a}} = \frac{\partial C_Y}{\partial \delta_a}$$

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta} \qquad C_{Z_{\delta e}} = \frac{\partial C_Z}{\partial \delta_e}$$

$$C_{n_\beta} = \frac{\partial C_n}{\partial \beta} \qquad C_{Y_r} = \frac{\partial C_Y}{\partial \frac{rb}{2V}}$$

Subscript:

0 initial condition and/or trim condition

Abbreviations:

ALT approach and landing tests

ANOV analysis of variance

DAC digital-to-analog converter

d.o.f. degrees of freedom

L.S.R. least significant range

PIO pilot-induced oscillation

rms root mean square

VMS visual-motion simulator

A dot over a quantity indicates a derivative with respect to time. A bar over a symbol of the seven tracking parameters and three audio-task parameters

indicates the arithmetic mean of the rms values for all runs having identical test conditions.

BACKGROUND INFORMATION

Included as a part of the Space-Shuttle-orbiter testing program was a series of five free-flight landings to be performed at the Edwards Flight Center. For these approach and landing tests (ALT) the orbiter was carried to launch altitude on top of a 747 airplane. For flights 1, 2, and 3 the orbiter was fitted with a tail cone that enclosed the rocket nozzles. The final two flights were made with the tail cone removed.

The first indication of a PIO problem occurred on landing number 5. This was the only landing to be made on a concrete runway, and touchdown was to be made at a particular spot. As the orbiter approached the runway, it was high and fast with respect to the nominal trajectory. The pilot was working the speed brake and using the pitch controller in order to attain the touchdown point. A pitch oscillation developed with the elevons operating at their maximum rate. As the shuttle settled to the runway, one wheel hit first introducing a roll disturbance. The pilot applied roll control. Because of the pitch commands, priority rate limiting (which exists in the software because of actuator hydraulic-fluid flow limitations) was encountered in the control system and aileron commands were locked out. After an interval approaching 800 msec, the ailerons deflected. These events triggered a PIO in roll. When the pilot released the hand controller the pitch and roll oscillations stopped.

In analyzing the flight records it was decided that the primary cause of the roll PIO was aileron command-signal lockout due to priority rate limiting. The remedy for this difficulty was to allow some roll-control authority at all times. In addition to this cause, other reasons for the occurrence of PIO's both in pitch and roll are believed to be the presence of time delay in the digital flight-control system and/or rate limiting of the control surfaces. Contributors of lesser importance could be the torque-deflection characteristics of the hand controller, some forward loop gains in the control system, the influence of the aerodynamic derivative $C_{L_{\delta,elevon}}$ (change in lift coefficient due to elevon deflection), and possibly specifying a particular touchdown spot. Of these various factors, only the effect of control-system time delays was examined in the present study.

DESCRIPTION OF APPARATUS

The tests reported herein were performed in the Langley visual-motion simulator (VMS) which is a hydraulically operated, six-legged synergistic motion base. (See fig. 2.) Six computed leg positions are used to drive the motion base. The computed leg extensions are passed from the computer to the motion base through digital-to-analog converters (DAC) every 31.25 msec. To eliminate the stair-stepping in this output and provide smooth continuous signals for driving the motion base, the DAC outputs are passed through notch filters on

the hardware. Filter characteristics are given in reference 5, and the transformations used to compute the leg extensions are derived in reference 6. References 5 and 7 give the performance limits of the VMS. The present study used the coordinated adaptive washout of reference 8. The equations and constants for the motion base were those listed in reference 9 except for four parameter values. (In the nomenclature of ref. 9, the four parameters and values are: $\lambda_y(0) = 1$, $\lambda_{y,max} = 1$, $\eta_z(0) = 0.4$, and $\eta_{z,min} = 0.4$.) The four values chosen provided improved base response for this study.

The pilot's compartment is representative of a two-man cockpit (fig. 3). Although the panel instruments were illuminated, they were not operational and were not required by the subjects. Visual cues of the target aircraft were generated by a small model and closed-circuit television. The model was mounted in a two-axis gimbal support that allowed rotation in pitch and yaw. Information on the relative motion between the orbiter and target aircraft drove the model so that the subject saw the proper aspect of the target. Target-aircraft roll was accomplished electronically by proper rotation of the television raster. Elevation and azimuth changes of the target aircraft in the display were obtained by repositioning the television raster electronically. The repositioning was accomplished by using scaled voltages to represent angles of deflection in elevation and azimuth. This technique eliminated unwanted delays in visual-scene display; such delays occur when electromechanical systems (involving mirrors, gears, and electric motors) are used to obtain elevation and azimuth positions. The image was displayed by use of a television screen (fig. 4) with an infinity optics mirror. The horizon was also projected on the screen. A reticle (two crossed lines) was projected on the center of the screen to represent sights on the vehicle flown by the subject.

The subject used a two-axis rotational hand controller to control rotations about the orbiter pitch and roll body axes. Torque-deflection characteristics are given in figure 5. The controller is shown in the photograph of figure 3. Note that the controller location (mounted to the side of the subject rather than in the center position), the curves of torque plotted against deflection, and the device itself differ from that used in the full-scale shuttle orbiter. The output signals of the hand controller, however, are passed through a quadratic shaper and are limited as is done in the actual shuttle orbiter so that curves of commanded rate plotted against handle deflection are similar. (See fig. 6.)

All equations of the simulation, except those for the audio task, were solved on a digital computer. The digital outputs were then converted to analog signals to drive the visual-scene and motion-generation equipment. The hardware at the Langley Research Center for computer-signal processing from analog to digital and back to analog can be represented mathematically as a prefilter, a computational delay, and a zero-order hold. The prefilter attenuates the analog input-signal high-frequency components to suppress "aliasing" during the analog-to-digital conversion. The computational delay is the delay associated with the input, the processing, and the output of the signal through the computer. Finally, a zero-order hold adds one-half the computing interval caused by the sample-hold characteristics. The last delay represents an average value for that portion of the equipment which includes the DAC. For the prefilter setting of this study, the described hardware characteristics create an average

time delay from input to output of 1.5 times the update interval. This delay has an average value of about 47 msec which becomes part of the delay in the visual-scene presentation. The delay due to the scene-generation equipment for elevation and azimuth line-of-sight angles to the target was small as was the delay due to the televised display of the scene to the subject. Motion-cue presentation, like the visual display, also has the 47-msec time delay. In addition, the motion-base mechanical drive system has the time lags after compensation that are described in reference 5. These motion-base lags are, of course, a function of frequency. The lags expressed as an equivalent time delay were of the order of 50 msec. (See table X in ref. 2 for further information.)

ORBITER MATH MODEL

In order to eliminate the time required to develop and validate a math model for the orbiter, the method outlined briefly in this paragraph was employed. A fixed-base, six-degree-of-freedom, man-in-the-loop Space-Shuttle-Orbiter Simulation was in existence at the Langley Research Center. This fixed-base simulation was developed to study various aspects of the orbiter guidance and control system through a range of operating conditions from deorbit through reentry to landing. (See ref. 10.) This simulation has been continually modified and updated as changes were made in the actual orbiter guidance-and-control software in order that the simulation remain current. This simulator had no visual display that could accommodate an out-of-the-window landing task or tracking task. Because of the lack of both a visual display and motion cues, the simulator was inappropriate for the study of pilot-induced oscillations. However, use was made of the orbiter math model of this simulation for an unusual application of parameter-identification technology. Pitch- and then roll-control inputs were introduced during a landing approach. Control inputs and the resulting vehicle motions were recorded on disc storage. By these data, effective derivatives were extracted by using the maximum-likelihood parameter-extraction techniques available at Langley. (See ref. 11.) Thus, the present simulator used parameters extracted from another simulation. The parameter values obtained are for the vehicle and flight-control-system combination. Thus, the parameters are effective derivatives for a closed-loop shuttle orbiter having perfect actuators with no rate limiting. (This required that priority rate limiting be eliminated.) Thus, all delays in the control system were eliminated. The equations used in the parameter-extraction model are, of course, the same equations used to represent the orbiter in the present simulation. These equations are given in appendix A. A detailed discussion of the process of orbiter-derivative determination, along with some time-history comparisons, is contained in appendix B. The flight conditions chosen were: (1) 300-knot velocity, (2) altitude near sea level, (3) speed brake deflected 50°, (4) body flap fully retracted, and (5) landing gear deployed.

PILOT'S TASK

Primary Task

The primary task, as in references 1 to 4, was to track a target aircraft that was maneuvered in altitude only. The target was initially offset 30.48 m

(100 ft) laterally and driven in altitude with a cosine wave of very low frequency. The oscillation had an amplitude of 121.92 m (400 ft) and a frequency of 0.052 rad/sec (a period of 2 min). Only the first half-cycle of the cosine wave is used for each run as a way of generating a crude approximation of a landing task. Range to the target was varied linearly with time. Range was 182.88 m (600 ft) at the initiation of a run and 91.44 m (300 ft) at the termination of the run. The reduction in range was chosen such that the target would grow in size until the wing span matched the width of the horizontal bar of the reticle. This was an attempt to induce the pilot to increase his gain as he normally does during a landing flare. The subject's task was to track the target as closely as possible. Simply defined, this was to place the cross hairs on the center of the target tail pipe. The pilot used a hand controller and could apply only pitch and roll commands to the simulated vehicle. Total run time was 60 sec.

Audio Side Task

The audio side task used to increase the subject's workload was an application of the critical instability tracking task of Jex and others (e.g., refs. 12, 13, and 14). The audio task used is depicted in figure 7. The task required that the subject try to maintain a constant 1200-Hz audio signal by operating a thumb wheel with his left hand. The thumb wheel revolved freely and was not spring loaded. The audio signal was driven with the output of an unstable first-order linear system over a range of 500 to 1900 Hz mechanized to be hard limited. The instability was set at a subcritical level to require frequent, but not continuous, attention. As was pointed out in reference 14, increasing the instability increases the attention required of the subject.

The audio task included a memory update in the form of a reference tone (1200 Hz) that was provided to the subject as a pulse of short duration at fixed intervals during the run. The time setting was adjustable depending on the subject and instability value. Typical values used were a 1/4-sec pulse duration at 10-sec intervals. Insertion of the reference tone was controlled by a switching circuit operated by the digital computer as indicated in figure 7.

All subjects used in the present study were known to have normal hearing. Reference 15 indicated that for normal hearing the just-noticeable difference in the frequency range around 1000 Hz is about 0.3 percent. Thus, subjects should be able to discriminate frequency changes of the order of 3 to 5 Hz.

SUBJECTS

Five test subjects were used in the investigation. The individuals are identified in the following table:

Subject	Identity	Comment on experience
A	Research test pilot	Was astronaut candidate
B	Research test pilot	
C	Astronaut	Flew full-scale shuttle orbiter during free-flight approach and landing tests
D	Astronaut	Participated in all piloted simulation studies during orbiter development
E	Simulation engineer	Was listed as subject A in time-delay studies of references 2, 3, and 4

TEST PROGRAM

The study consisted of making simulated air-to-air tracking flights with a linearized version of the orbiter vehicle and control-system combination. Numerical values of the parameters used in the equations of motion to represent the orbiter configuration are given in table I. The equations are given in appendix A. Simulator runs, each of 60-sec duration, were made by using the same set of initial conditions. Only the sign on target lateral offset was altered run to run for variability.

A summary of the test configurations for each subject is given in the following table:

Subject	Identify	No side task (a)	With side task (a)	Side task only (a)
A	Research pilot	X	X	X
B	Research pilot	X	X	X
C	Astronaut	X	-	-
D	Astronaut	X	-	-
E	Engineer	X	X	X

[a]The letter X denotes that the configuration was tested; the dash - denotes it was not tested.

Because the time for astronaut participation was limited, the primary tracking task without the use of the audio side task was selected as the best test configuration to meet the time constraint. Tests with the side task were made by the two research pilots and the engineer to permit data comparisons with a test situation in which the subjects were known to be operating at their full capacity. Values of time delay were inserted into the simulation immediately following the hand-controller signals. Delay values of 0, 4, 8, 12, and 16 units were used. Each unit represents a time increment of 31.25 msec which is the update interval of the digital computer used. These units correspond to delays of 0, 125, 250, 375, and 500 msec, respectively. For subjects A, D, and E 20 units of delay (625 msec) were also used. The same value of time delay was inserted in both the pitch- and roll-control channels. Six simulation runs were made for each value of time delay by each subject. The different time-delay values were presented for testing by using a Latin square design. Tests were made with the motion base active. Runs made with the side task only were obtained under fixed-base conditions. In addition to this basic program, some supplemental tests were made by using subject B to examine briefly the effect of inserting unequal delay values in the pitch- and roll-control channels.

RECORDED DATA

Time-history records of a number of variables were obtained for every simulator run. Also, brief notes were taken of subject comments at run termination. For certain runs, pilot ratings using the Cooper-Harper scale were obtained. For each run rms values were computed for a number of selected parameters as shown in the following table:

Task	Symbols	Parameter
Primary task	$\bar{\eta}$	Elevation line-of-sight angle
	$\bar{\xi}$	Azimuth line-of-sight angle
	$\bar{\epsilon}_v$	Vertical displacement
	$\bar{\epsilon}_h$	Lateral displacement
	$\bar{\epsilon}_v + \bar{\epsilon}_h$	Sum of vertical and lateral displacements
	$\bar{\delta}_e$	Pitch-control input
	$\bar{\delta}_a$	Roll-control input
Side task	$\bar{B}$	Audio tone error
	$\bar{\delta}_s$	Audio thumb-wheel input
	$\bar{K}_*$	Side-task pilot gain

Three rms values were obtained for each parameter for each run. The rms values were obtained separately for the first 30 sec of the run, the last 30 sec of the run, and a total value for the complete 60-sec run.

Upon completion of the test schedule a debriefing was held for all subjects except E, since E helped formulate the questionnaire. Most of the questions and a composite of responses are given in appendix C. Included were requests for pilot ratings for various test conditions. Note that the questionnaire given subject A was fairly short. He was the first subject used in the simulation and completed the test program prior to the arrival of the astronauts. The questionnaire was expanded following his participation.

RESULTS AND DISCUSSION

General Remarks

Time histories of a single flight performed by subject B, showing motion-base response under PIO conditions, are presented for reference in figure 8. A value of added time delay of 500 msec was inserted in both the pitch- and roll-control channels. The audio side task was not used. For this particular flight a comparison of motion-base commands with the computed flight data obtained from the equations of motion is given in figure 9. This particular run was selected because it showed considerable motion of the base due to the difficulty that the subject experienced with the task.

The basic study conducted herein involved the two astronauts, the two research pilots, and the one engineer using the primary task only. The purpose was to determine the effect of control-system time delays on three factors:

(1) PIO occurrence
(2) Vehicle handling qualities
(3) Tracking performance

The additional tests with the side task for the two research pilots and engineer were included to establish the effect of time delay when the subjects were known to be fully occupied. The possibility that the pilot has some reserve capability on which to draw when the value of time delay was increased from zero is, thus, eliminated for these latter tests. Differences in the data for tests with and without the side task can then be explained. For the side task to be used properly some effort was made to establish the subject's workload prior to the insertion of additional values of time delay. Appendix D discusses workload establishment and presents the data for the three subjects.

PIO Occurrence

Following each simulator run the subjects designated whether or not a PIO occurred, which channel (pitch or roll) was involved, and when the PIO occurred during the run. The time-history records were examined for verification. Results were then assembled in tabular form for the different subjects, time-delay values, and test configurations examined. Figure 10 presents a chart

illustrating the frequency of PIO occurrence. No distinction is made as to whether the PIO occurred longitudinally or laterally. However, if a PIO occurred at the large delay values, both a longitudinal and lateral PIO usually occurred. The tabulated results also indicated no PIO's at the low values of delay although all subjects reported that they could detect the presence of the delay. At about 250 msec of added time delay PIO's began to occur. Estimation of the delay present in the orbiter flight-control system during the approach and landing tests (ALT) roughly corresponds to this value of added time delay in this simulation. A comparison of the research pilots' results with and without the audio task indicates a tendency for the number of PIO's to increase at a given delay value and/or to occur at a lower delay value when the side task was employed. Also, figure 10 indicates for all data that increasing time delay above 250 msec generally resulted in an increase in PIO occurrence.

Time-history traces are presented in figures 11 and 12 for several subjects to illustrate typical longitudinal and lateral PIO's for this task. Traces for the zero time-delay case are also given to show no pilot-induced oscillations. For the longitudinal case (fig. 11) oscillations of increasing amplitude appear in the pitch attitude and angle of attack. In the lateral case (fig. 12) similar oscillations usually were detected in line-of-sight angle ξ, control input δ_a, and in angular rate $\dot{\varphi}$. These oscillations were identified verbally as PIO's by the subjects. Most of the PIO's encountered in these tests occurred near the end of the run. Some instances did occur, however, where the PIO was generated about half way through the run. These were usually in the lateral channel. In such situations the normal remedy was to release the controls until the situation stabilized. Note that this was also the technique used by subject D at large delays, such as for τ = 500 msec, and is the reason why so few fully developed PIO's were recorded for this subject. (See fig. 10.)

Simulated Vehicle Handling Qualities

Some assessment of the simulated vehicle handling qualities for the tracking task was obtained through the use of pilot ratings and pilot comments. Only the astronauts and research pilots participated in this evaluation. Pilot ratings were obtained by using the Cooper-Harper rating scale given in figure 13. (See ref. 16.) Subjects were asked for ratings during the test sessions following runs at specific delay values. Ratings were again requested as a cross-check during the debriefing session. Figure 14 summarized these results. Three of the subjects (A, B, and D) gave only one overall value for each condition. Subject C, however, gave two values for each condition. The first value was associated with the pitch control, and the second with the roll control. In addition to designating PIO occurrence, pilot comments were solicited at various times during the tests. Also, a questionnaire was employed for the debriefing session that requested detailed comments. Appendix C contains most of the questions appearing on the debriefing questionnaire and a composite of the replies.

Figure 14 shows that for the zero time-delay condition pilots gave overall ratings of 3 which is in the satisfactory region on the handling-qualities chart. With an increase in time delay pilot ratings increase indicating, of

course, degraded handling qualities with increasing delay. Values of pilot ratings of 4-1/2 to 6 for 250 msec of delay indicate some need for improvement for this particular tracking task. Note that this value of delay approximates that estimated for the shuttle orbiter during the free-flight approach and landing tests. When the side task was added, subjects gave poorer pilot ratings by generally 1 to 2 units across the range of time delays. This is an obvious indication of a very high workload situation for the combined task.

Astronauts' comments on the simulated vehicle were that it seemed reasonably close to a 300-knot orbiter. Although the hand controller in the simulator differed from that in the shuttle orbiter, the astronauts felt that the effect on this time-delay study was of second order. All subjects commented that the lateral tracking task was more troublesome than vertical tracking. Difficulties resulting in PIO's, however, were obtained in both channels. Most of the difficulties in handling qualities were found to occur near the end of the run. In addition, the difficulties increased as time delay increased. For a more detailed discussion, see appendix C.

Pilot Tracking Performance

The basic experiment involved two factors, time delay and subjects. The effects of these factors are examined here on only four of the various primary-task variables recorded. Elevation line-of-sight angle for total run time and azimuth line-of-sight angle for the last 30-sec segment of the run are the two tracking measures considered. These two were selected since they are associated with close tracking. Note that azimuth angle, for the first 30-sec run segment, experienced large changes since this was primarily a target acquisition phase and, therefore, was omitted. The remaining two variables are hand-controller inputs for pitch and roll control for the complete run. For tests with the audio task, the three side-task parameters $\bar{B}$, $\bar{\delta}_s$, and $\bar{K}_*$ are presented. An examination of all the task variables recorded for each of the run segments (first 30-sec segment, last 30-sec segment, and total 60-sec segment) was carried out. These results are omitted here but are discussed in appendix E.

Statistical analysis with no side task.- A two-way analysis of variance (ANOV) for time delay and subject effects with no side task is presented in table II. The line-of-sight angles and controller inputs show time-delay effects and subject effects that are statistically significant at the 5-percent level. In addition, the elevation angle and the roll-control input show significant interaction between the delay and subjects. Since the ANOV indicates that both time delay and subjects are significant factors, t-tests and Duncan multiple-range tests (see ref. 17) were performed to see which levels of each factor were significantly different at the 5-percent level. It should be noted that the standard error used in the t-tests for time delay was based on data pooled over all time delays for a given subject. In like manner, the standard error used in the Duncan multiple-range test for subject effects was based on data pooled over all subjects for a given time delay.

Time-delay effects with no side task.- Means, standard deviations, and t-test values for time-delay effects are presented in table III, and the mean

values of the performance measures for all subjects are plotted as functions of time delay in figure 15 for the no-side-task condition. Each point represents the mean of six data runs, and the fairing is used to help visualize the statistical significance of the time delays. If the second data point, plotted at 125 msec, is not significantly different from the zero delay point at the 5-percent level, the line continues at the original value. For each larger time delay, the line continues until the 5-percent significance level is reached, at which time the line is drawn to the data point. The main purpose of the fairing is to show the breakpoint at which the performance begins to degrade. Consequently, the lines are not extended beyond the first significantly different data point even though the t-test was applied at all time delays. Increasing time delay generally causes a degradation in pilot performance. The breakpoint in the rms elevation and azimuth line-of-sight angles occurs at 250 msec for four of the subjects. The subjects' pitch-control inputs also show a breakpoint at 250 msec whereas their use of the roll control was altered after 125 msec. The lower breakpoint value for roll control for these four subjects was believed to result because of the inclusion of the data for the first 30 sec of the run. For all performance measures, subject E, the research engineer, had performance that degraded at 375 msec. The primary reason that subject E was able to tolerate larger delays before his performance degraded was because he made pulse-type control inputs rather than continuous inputs. This type of input gives the subject a better capability to detect and evaluate time delays. Subject D used the same technique but to a lesser extent. Both subjects D and E tended to use continuous-type inputs when no delays were present. (See ref. 2 for related experience.) It is worth observing that the location of the breakpoint in the line-of-sight angles, which are the principal task-performance measures, agrees quite well with the added delay value for the appearance of PIO's for all of the subjects.

Subject effects with no side task.- The Duncan multiple-range tests (ref. 17) for subject effects with no side task are presented in table IV. The rms azimuth-angle results are not tested because the ANOV (table II) indicated no subject effect on azimuth angle. There are significant interaction effects between subjects and time delay for both elevation line-of-sight angle and roll-control inputs as indicated by the ANOV. In the case of elevation angle, subject A generally has significantly larger rms values than the other subjects for time delays up to 250 msec (table IV); whereas at the larger delays subject E tended to have smaller values than some of the other subjects. The subject effects are less consistent for roll-control inputs. However, subject C generally used significantly larger roll-control inputs at all time delays, and subject B used larger inputs at large delays than did the other subjects. Pitch-control inputs show a subject effect only at zero added delay where subjects C and E have inputs that are significantly larger than the other subjects.

Statistical analysis with side task.- A two-way analysis of variance (ANOV) for time delay and subject effects when using the side task is presented in table V. Both the primary-task performance measures and the side-task performance measures show time-delay effects that are significant at the 5-percent level. In addition, all performance measures except azimuth line-of-sight

angle and roll-control input show significant subject effects for the three subjects who used the audio side task.

Time-delay effects with side task.- Means, standard deviations, and t-test values for time-delay effects are presented in table VI, and the mean values of the performance measures are plotted as functions of time delay in figure 16. The effect of time delay in pilot performance with the side task is quite similar to that experienced without the side task. One exception is subject B whose elevation-angle results degrade 125 msec sooner (at 125 msec) than was the case for no side task even though subject B began to use larger pitch-control inputs 125 msec sooner in an attempt to keep the elevation line-of-sight angle small. The other exception is that all three subjects who used the audio task exhibited breakpoints in roll-control inputs that occur at larger time delays than when they had no side task to perform. It is believed that this is because the subjects did not track azimuth angle as tightly when the side task was included. (Compare azimuth-angle levels with and without side task.) The error in tracking the audio signal of the side task degrades at 250 msec for subject B and at 375 msec for subjects A and E. In addition, the pilot gain achieved by subject B degrades at 250 msec, whereas that of subject A degrades at 375 msec. Subject E was able to maintain the same value of pilot gain over all time delays.

Subject effects with side task.- The Duncan multiple-range tests (ref. 17) for subject effects when using the audio side task are presented in table VII. The greatest subject difference occurs in pilot gain $\bar{K}_*$ in which subject E achieved much larger pilot-gain values than either subjects A or B. This was expected because of the form of the unstable first-order system programed (see ref. 3) and the values of the instability λ used for the subjects. Even with a more difficult task, subject E is able to maintain an error in the audio signal that is generally smaller than subject A or B. Another significant subject difference occurs in the elevation angle where subject A has a significantly larger error than either subject B or E.

Performance delay assessment.- Of the various parameters previously discussed, the two of major consequence in a performance assessment are the azimuth and elevation line-of-sight angles. It was these two parameters that the subjects were continuously attempting to null. Only the breakpoints for the line-of-sight angles need be considered since these entities embody the statistical analysis of the time-delay effect. For the no-side-task condition (see fig. 15), the time-delay breakpoint occurs at 250 msec for the two astronauts and the two research pilots. Only the breakpoint for subject E differed and this occurred at 375 msec. In addition, the breakpoint occurred at the same delay value for both line-of-sight angles for each subject. It is interesting to observe that the breakpoint at 250 msec for the four pilot subjects is the delay value at which PIO's were first encountered. (See fig. 10.) During the tests with no side task several subjects commented on the high workload at the end of the run when large values of added time delay were present. For these tests, however, no constraints were placed on task loading. Therefore, as time delay increased the subject could work harder. The tests made with the side task provided a control on task loading for the three subjects. Results show that for subjects B and E the time-delay breakpoint was the same value for one line-of-sight angle as for the no-side-task case. For the other

line-of-sight angle, however, the breakpoint was 125 msec less than for the no side-task case.

Thus, it appears that subjects using the side task and known to be operating at their full capacity at all delays show breakpoints somewhat less than when tested with no side task. The inference of the proceeding comments is that, for this particular tracking task, added delays of no more than 125 msec in each control channel would eliminate PIO's and still show no degradation statistically in tracking performance. Extrapolation of these results to the landing task, however, requires further study.

Supplemental Tests

Tests of the basic study were performed with the same value of added time delay inserted in the pitch- and roll-control channels. For the actual shuttle orbiter, however, such a situation need not occur. Therefore, some tests were performed by using a mismatched set of delays. Data were obtained with a constant delay in the roll channel and varying amounts of delay in the pitch channel. Because all subjects felt the lateral tracking task was the more troublesome of the two, the value of τ_r was chosen to be less than that corresponding to initial PIO occurrence in the basic study. The value of τ_r selected was 125 msec (τ_r = 4 units). This choice for τ_r represents, of course, a reduction in the delay present in the particular shuttle-orbiter configuration considered herein. As mentioned previously, the astronauts indicated a reasonable match of the simulator with a 300-knot orbiter when $\tau_r = \tau_p = 250$ msec.

Results obtained for subject B are given in figure 17 and compared with the data for equal delay values in both control channels. The figure shows that PIO tendencies still exist for the mismatched delay condition; however, PIO's were initially encountered at 375 msec rather than at 250 msec of delay. With mismatched delays, the number of PIO's at a given delay was smaller and, in addition, the PIO's encountered were all pitch PIO's. Even so, the pilot ratings given by subject B show little difference between the two conditions. (See appendix C for subject comments.) Tracking performance, however, showed an improvement in rms elevation and azimuth line-of-sight angles at the larger delays. As a consequence, the degradation in tracking performance depicted by the breakpoint in the statistical analysis was shifted to a larger delay value for the mismatched condition.

The major implication of these results is that reducing the task difficulty in one channel yields a reduction in PIO occurrence and improvement in tracking performance in the other channel. For the Space-Shuttle orbiter, therefore, any reduction that can be made in the time delay present in either control channel will result in an improvement in PIO tendency and tracking performances in both channels.

CONCLUSIONS

A brief experimental study using the Langley visual-motion simulator has been made to determine the effect of control-system time delays on pilot-induced

oscillation (PIO) occurrence, vehicle handling qualities, and pilot tracking performance for a landing-approach configuration of a Space-Shuttle-orbiter configuration. A linearized math model was employed which represented the orbiter vehicle and control-system combination with almost all control-system time delays removed. Additional time delays were then inserted immediately following the pilot's hand-controller signals. Only pitch and roll commands were used for vehicle control. Identical delay magnitudes were inserted in both control channels. The simulation employed an air-to-air tracking task as a means of emphasizing PIO tendencies. Tracking runs of 60-sec duration were performed in which target altitude was varied as a cosine function, and range to the target was reduced linearly from 182.88 m (600 ft) to 91.44 m (300 ft). Two astronauts, two research pilots, and one experienced simulation engineer were used as test subjects. An audio side task was used for some tests by several subjects to assure that they were fully occupied at all times. Results of the study indicated the following conclusions:

1. Astronauts indicated the simulated vehicle approximated a 300-knot shuttle orbiter when 250 msec of time delay (estimated for the orbiter used in the approach and landing tests) was added to both channels of the control system.

2. PIO's were found to occur longitudinally and/or laterally near the end of the tracking runs (at reduced range) when time delays of 250 msec or more were added to both the pitch and roll channels of the control system of the simulated vehicle.

3. Assessment of vehicle handling qualities using pilot ratings indicated that with zero added time delay the simulated vehicle had satisfactory ratings. Increasing time delay degraded the vehicle handling qualities. For an added time delay of 250 msec the pilot ratings were at a level suggesting need for improvement for this particular tracking task.

4. The rms tracking results for azimuth and elevation line-of-sight angles indicated that a performance degradation occurs when added time delays inserted in the control system exceed 250 msec. Results with the side task were similar for azimuth angle; however, one subject showed an elevation-angle degradation after only 125 msec of delay was added.

5. Data for mismatched delays indicated that reducing the task difficulty in one channel (i.e., reducing the delay value) yielded a reduction in PIO occurrence and an improved tracking performance in both channels.

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January 2, 1980

APPENDIX A

EQUATIONS OF MOTION

The equations used in this study for the Space-Shuttle orbiter are written about the body axes and are as follows:

Aerodynamic force terms:

$$a_X = \frac{\frac{1}{2}\rho V^2 S}{m}\left(C_{X,0} + C_{X_\alpha}\Delta\alpha\right) \tag{A1}$$

$$a_Y = \frac{\frac{1}{2}\rho V^2 S}{m}\left(C_{Y_\beta}\beta + C_{Y_p}\frac{pb}{2V} + C_{Y_{\delta a}}\delta_a\right) \tag{A2}$$

$$a_Z = \frac{\frac{1}{2}\rho V^2 S}{m}\left(C_{Z,0} + C_{Z_\alpha}\Delta\alpha + C_{Z_q}\frac{q\bar{c}}{2V} + C_{Z_{\delta e}}\delta_e\right) \tag{A3}$$

Rotational equations of motion:

$$\dot{p} = \dot{r}\frac{I_{XZ}}{I_X} - qr\frac{I_Z - I_Y}{I_X} + \frac{pqI_{XZ}}{I_X} + \frac{1}{2}\frac{\rho V^2 Sb}{I_X}\left(C_{l_\beta}\beta + C_{l_r}\frac{rb}{2V} + C_{l_p}\frac{pb}{2V} + C_{l_{\delta a}}\delta_a\right) \tag{A4}$$

$$\dot{q} = -pr\frac{I_X - I_Z}{I_Y} + r^2\frac{I_{XZ}}{I_Y} - p^2\frac{I_{XZ}}{I_Y} + \frac{1}{2}\frac{\rho V^2 S\bar{c}}{I_Y}\left(C_{m,0} + C_{m_\alpha}\Delta\alpha + C_{m_q}\frac{q\bar{c}}{2V} + C_{m_{\delta e}}\delta_e\right) \tag{A5}$$

$$\dot{r} = \dot{p}\frac{I_{XZ}}{I_Z} - pq\frac{I_Y - I_X}{I_Z} - qr\frac{I_{XZ}}{I_Z} + \frac{1}{2}\frac{\rho V^2 Sb}{I_Z}\left(C_{n_\beta}\beta + C_{n_p}\frac{pb}{2V} + C_{n_r}\frac{rb}{2V} + C_{n_{\delta a}}\delta_a\right) \tag{A6}$$

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In equations (A1) to (A6),

$$\Delta\alpha = \alpha - \alpha_t$$

$$\alpha = \tan^{-1} \frac{w}{u}$$

$$\beta = \sin^{-1} \frac{v}{V}$$

$$V = \left(V_x^2 + V_y^2 + V_z^2\right)^{1/2}$$

and

$$u = \ell_1 V_x + \ell_2 V_y + \ell_3 V_z$$

$$v = m_1 V_x + m_2 V_y + m_3 V_z$$

$$w = n_1 V_x + n_2 V_y + n_3 V_z$$

The orbiter's orientation and velocity relative to inertial coordinates (assuming a flat Earth) are required to generate the proper position of the target relative to the orbiter. The orientation of the orbiter is specified by Euler angles. These are determined from body angular rates by

$$\dot{\varphi} = p + q \sin \varphi \tan \theta + r \cos \varphi \tan \theta$$

$$\dot{\theta} = q \cos \varphi - r \sin \varphi$$

$$\dot{\psi} = (r \cos \varphi + q \sin \varphi) \frac{1}{\cos \theta}$$

Inertial accelerations are given by

$$\dot{V}_x = \ell_1 a_X + m_1 a_Y + n_1 a_Z$$

$$\dot{V}_y = \ell_2 a_X + m_2 a_Y + n_2 a_Z$$

$$\dot{V}_z = \ell_3 a_X + m_3 a_Y + n_3 a_Z + g$$

Direction cosines are defined as follows:

$$\ell_1 = \cos\psi \cos\theta$$

$$\ell_2 = \sin\psi \cos\theta$$

$$\ell_3 = -\sin\theta$$

$$m_1 = \cos\psi \sin\theta \sin\varphi - \sin\psi \cos\varphi$$

$$m_2 = \sin\psi \sin\theta \sin\varphi + \cos\psi \cos\varphi$$

$$m_3 = \cos\theta \sin\varphi$$

$$n_1 = \cos\psi \sin\theta \cos\varphi + \sin\psi \sin\varphi$$

$$n_2 = \sin\psi \sin\theta \cos\varphi - \cos\psi \sin\varphi$$

$$n_3 = \cos\theta \cos\varphi$$

Initial conditions used were $\rho = 1.22571$ kg/m^3 (0.002378 slug/ft^3); $V_{x,0} = 152.40$ m/sec (500 ft/sec); $V_{y,0} = V_{z,0} = 0$; $\psi_0 = \theta_0 = \varphi_0 = 0$; and $p_0 = q_0 = r_0 = 0$. For trimmed flight

$$C_{m,0} = 0$$

$$C_{X,0} = 0$$

$$C_{Z,0} = \frac{-mg}{\frac{1}{2}\rho V_0^2 S}$$

All simulator runs were started with these derivative values.

APPENDIX B

ORBITER DERIVATIVE DETERMINATION

The method employed herein to model the Space-Shuttle orbiter was to use an existing fixed-base orbiter simulation and an existing parameter-extraction computer routine in order to obtain effective derivatives for the orbiter vehicle and control-system combination.

The base-line configuration had the following characteristics:

(a) No priority rate limiting

(b) Perfect actuators with no rate limiting

(c) Body flap retracted

(d) Speed brake deflected 50°

(e) Landing gear deployed

Several simulator runs were made in which pulse-type inputs in pitch and roll were applied. Since the control system was active, pulse inputs of 1-sec duration were made in the hand-controller signals instead of elevon deflection. The simulator runs were started with the following landing-approach conditions:

$\theta = -17.56^{\circ}$

$\alpha = 4.325^{\circ}$

$V = 158.06$ m/sec (518.57 ft/sec)

$h = 1200.24$ m (3937.79 ft)

For each run, a number of motion variables and controller inputs were recorded on disc storage. These variables served as inputs to the parameter-extraction program. Run times were 6 to 8 sec. These runs were of sufficient length to permit parameter evaluation.

The parameter-extraction program of reference 13 was used to establish numerical values for the various effective derivatives. This program employed a conventional-airplane math model and equations of motion written about the body axes. The equations used were the following parameter-extraction equations:

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$$\dot{u} = -qw + rv - g \sin \theta + \frac{\frac{1}{2}\rho V^2 S}{m}\left[C_{X,0} + C_{X_\alpha}(\alpha - \alpha_t)\right]$$

$$\dot{v} = -ru + pw + g \cos \theta \sin \varphi + \frac{\frac{1}{2}\rho V^2 S}{m}\left[C_{Y,0} + C_{Y_\beta}\beta + C_{Y_p}\frac{pb}{2V} + C_{Y_{\delta a}}\delta_a\right]$$

$$\dot{w} = -pv + qu + g \cos \theta \cos \varphi + \frac{\frac{1}{2}\rho V^2 S}{m}\left[C_{Z,0} + C_{Z_\alpha}(\alpha - \alpha_t) + C_{Z_q}\frac{q\bar{c}}{2V} + C_{Z_{\delta e}}\delta_e\right]$$

$$\dot{p} = \dot{r}\frac{I_{XZ}}{I_X} - qr\frac{I_Z - I_Y}{I_X} + pq\frac{I_{XZ}}{I_X} + \frac{\frac{1}{2}\rho V^2 Sb}{I_X}\left[C_{l,0} + C_{l_\beta}\beta\right.$$

$$\left. + C_{l_r}\frac{rb}{2V} + C_{l_p}\frac{pb}{2V} + C_{l_{\delta a}}\delta_a\right]$$

$$\dot{q} = -pr\frac{I_X - I_Z}{I_Y} + r^2\frac{I_{XZ}}{I_Y} - p^2\frac{I_{XZ}}{I_Y} + \frac{\frac{1}{2}\rho V^2 S\bar{c}}{I_Y}\left[C_{m,0} + C_{m_\alpha}(\alpha - \alpha_t)\right.$$

$$\left. + C_{m_q}\frac{q\bar{c}}{2V} + C_{m_{\delta e}}\delta_e\right]$$

$$\dot{r} = \dot{p}\frac{I_{XZ}}{I_Z} - pq\frac{I_Y - I_X}{I_Z} - qr\frac{I_{XZ}}{I_Z} + \frac{\frac{1}{2}\rho V^2 Sb}{I_Z}\left[C_{n,0} + C_{n_\beta}\beta\right.$$

$$\left. + C_{n_r}\frac{rb}{2V} + C_{n_p}\frac{pb}{2V} + C_{n_{\delta a}}\delta_a\right]$$

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In applying the program several derivatives such as C_{Y_r} which normally appear in the equations were set to zero and held constant. As a consequence, these terms, since they were inactive, were dropped from the aforementioned equations since an initial extraction attempt indicated extremely small magnitudes for these derivatives. The derivative contributions due to angle of attack appear in the equations multiplied by the increment in angle of attack from some trim value. The trim angle of attack α_t in the equations was chosen as the α that existed at the start of the run ($\alpha_t = 4.325^\circ$). In applying the extraction program the aforementioned equations were divided into two sets: one for longitudinal motions and one for lateral motions.

For longitudinal motions only the equations for $\dot{u}$, $\dot{w}$, and $\dot{q}$ were used. In addition, the values for r, p, v, and φ were set to zero and held fixed. Also, the hand-controller input was only a pitch pulse. The numerical values extracted were as follows:

$C_{X,0} = -0.0711$	$C_{Z,0} = -0.2320$	$C_{m,0} = -0.0015$
$C_{X_\alpha} = 0.3384$	$C_{Z_\alpha} = -3.4490$	$C_{m_\alpha} = -0.0253$
	$C_{Z_q} = -17.5013$	$C_{m_q} = -16.4431$
	$C_{Z_{\delta e}} = 0.5744$	$C_{m_{\delta e}} = 0.2922$

Time-history traces comparing several simulation variables with traces computed by using the aforementioned derivative values for the same controller input are given in figure 18. The terms a_X and a_Z plotted in figure 18 are the aerodynamic contributions appearing in the $\dot{u}$ and $\dot{w}$ equations. (See also eqs. (A1) and (A3).) The controller input in both cases as shown in figure 18 was a pulse inserted at $t = 1$ sec and removed at $t = 2$ sec.

For lateral motions only the equations for $\dot{v}$, $\dot{p}$, and $\dot{r}$ were used. Note that for the lateral case the values for the longitudinal-motion variables u, w, and θ that were recorded on disc storage were used in the equations during the extraction process. The hand-controller input signal used as the disturbance was a single-roll pulse of 1-sec duration. This pulse was inserted at $t = 1$ sec as was done in the longitudinal case. The numerical values extracted were as follows:

$C_{Y,0} = 0.00001$	$C_{l,0} = -0.00007$	$C_{n,0} = 0.00022$
$C_{Y_\beta} = -4.8484$	$C_{l_\beta} = 0.1518$	$C_{n_\beta} = 0.8309$

$C_{l_r} = 0.1070$ $C_{n_r} = -1.3931$

$C_{Y_p} = 0.1323$ $C_{l_p} = -0.3422$ $C_{n_p} = 0.2717$

$C_{Y_{\delta a}} = -0.0292$ $C_{l_{\delta a}} = 0.0265$ $C_{n_{\delta a}} = 0.0004$

Time-history traces comparing several simulation variables with traces computed by using these derivative values for the same controller roll input are given in figure 19.

The extraction program used employs an iterative technique to arrive at the best match between the reference and computed time histories. This scheme requires several passes through the program. Following each pass an adjustment is made to the derivative values. This continues until a performance criterion is minimized. The computed time histories in figures 18 and 19 represent the best match for the mathematical model specified.

APPENDIX C

DEBRIEFING QUESTIONNAIRE AND COMPOSITE

OF REPLIES

Questions presented to the astronauts and research pilots during debriefing and a composite of the answers and/or pertinent comments are as follows:

(1) Is the task a reasonable one for examining orbiter PIO's due to the presence of system time delays?

<u>Subject C</u>: The task points out the tendency for PIO's as time delay increases. It is hard, however, to relate this task directly to the landing PIO problem.

<u>Subject D</u>: One might be able to draw some conclusions from this task; however, you'd have to be very judicious in interpreting the results. It is true that formation tasks tend to get your gains up; and if you have trouble flying these tasks, then you will uncover some characteristics that perhaps may give trouble in the landing task. How much trouble, however, is difficult to estimate. It would certainly point out that a problem exists with the flight control system for rapid precise inputs. The formation task is also instructive in giving an idea of one's tolerances with the particular system to the effects of delays.

(2) Does a PIO tendency exist: (a) Longitudinally? (b) Laterally?

Mode	Subject			
	A	B	C	D
Longitudinal	Yes	Yes	Yes	Yes
Lateral	Yes	Yes	Yes	Yes

(3) If so, at what value of time delay (in units) does this become noticeable: (a) Longitudinally? (b) Laterally? (Note that 1 unit of time delay is equal to 31.25 msec.)

Mode	Time delay for subject -			
	A	B	C	D
Longitudinal	16	12		
Lateral	8	8		

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All subjects stated that they could detect the presence of time delay upon insertion of the first increment (4 units).

(4) Which is more susceptible to PIO - the longitudinal task or the lateral task?

<u>All subjects</u>: The lateral task.

(5) In performing the primary task, which is the more difficult - the longitudinal task or the lateral task? Does this apply for all time delays?

<u>All subjects</u>: Lateral task at all delays.

Subject A commented that stopping lateral translation is the problem.

Subject B commented that only in the case of very large delays (16 or 20 units), with a large vertical tracking error occurring near the end of the run, would the longitudinal task become more difficult than the lateral task.

Subject D commented that the lateral task was more difficult even at zero delay. On occasion he had a tendency to overcontrol and get a little wing wobble.

(6) Does the simulation provide adequate representation of the Space-Shuttle orbiter?

> <u>Subject C</u>: The stick is different. It feels different and the grip is different. Also, it is positioned off to the side where our stick is in the middle. Our stick is cocked off 19° to aline with your forearm when sitting in the seat with your elbow on your leg. Our new stick has heavier forces so it feels different. Now the vehicle response to control input is probably pretty close if this is supposed to be a 300-knot orbiter. I have to keep thinking about airspeed because the orbiter responds differently as it slows down. If there is any difference, I would say it seems to be a little snappier in response to roll. It is essentially deadbeat and the orbiter is that way so it's not dramatically different. It is reasonably close as near as I can tell.
>
> <u>Subject D</u>: The type of responses are not unlike those I've seen in other orbiter simulators. It is masked by the stick. The stick wasn't comfortable for me and was not like flying the orbiter stick.

(7) At what time delay does this simulator best represent the orbiter?

> <u>Subject D</u>: My impression is somewhere around 8 units. This seems to be in the ball park with other simulations I've seen. With the OFT versions (orbital flight trainer) I would guess somewhere between 4 and 8 units, but pushing closer to 8 units.

(8) For this task is the control power adequate: (a) In pitch? (b) In roll?

Subjects B, C, and D: Adequate in pitch.

Subject B: Adequate in roll for large deflections but possibly not for small deflections. I think this reflects the nonlinearity of the controller output. A fairly low gradient - not force gradient but output gradient - exists around the trim position so that it is hard to make small inputs. Thus, you wind up overcontrolling just a little. This was noticeable even at the zero delay case.

Subject C: Adequate in roll.

Subject D: Adequate in roll - in fact, control power may be a little more than you'd want in the small input range.

(9) For this task are the hand-controller torque-deflection characteristics adequate in pitch and in roll?

All subjects: Pitch adequate; roll inadequate. Suggestions for improvement: (1) Increase torque-deflection gradient in roll control since it is fairly low; (2) include damping in hand-controller roll axis.

Comment: Low torque gradient and no damping coupled with nonlinear output may have aggravated some of the PIO tendencies.

(10) The maximum deflection in pitch available in the hand controller of this simulation is less than that available in the shuttle. Was the maximum deflection in pitch adequate for this task? Did you ever employ full-pitch hand-controller deflection?

All subjects indicated that available deflection in pitch was considerably more than that required for normal control. Several subjects said they never used maximum controller deflection. The others indicated that hitting the pitch stop might possibly have occurred on infrequent occasions during aggressive control applications or possibly in a PIO.

(11) If the orbiter hand controller had been used in the simulation would it have: (a) Improved your tracking performance? (b) Reduced PIO tendencies?

(a) Subjects C and D expected some improvement would occur in roll-channel tracking.

(b) Subjects C and D believed roll PIO tendencies would be reduced.

General comment: A larger level of roll difficulty was encountered in this simulation than in other orbiter simulators flown.

(12) Do you feel that reasonable changes in hand-controller characteristics (i.e., of the order of 20 percent) would change your basic feeling about PIO's due to the presence of time delays?

Subject B: It is difficult to evaluate 20 percent as a quantitative value. As indicated earlier, some increase in force characteristics in the roll axis would be beneficial. Whether a 20-percent increase would do it or not would have to be evaluated with further testing.

Subject C: I don't know whether 20 percent is noticeable or not. The controller is not the basic cause of the problem - it's the presence of time delays. Changing the hand-controller characteristics won't solve the basic problem - at least not completely.

Subject D: Increasing the stick-force gradient helps to reduce the PIO tendency because it slows the pilot down a little bit. Thus, a trend does exist but I couldn't quantify it. It would have to be tested.

(13) Do you ever use combined control inputs or are pitch and roll commands inserted sequentially?

Subject A: Mostly use single inputs, that is, one axis at a time. For this task I can keep the control inputs separated. Instances do occur, however, when combined controls can be used conveniently. (For example, with a lateral-control input in one can put in a little pitch control.)

Subject B: For the most part they are inserted sequentially. At large delays I use a more or less bang-bang technique. At low delays (τ = 0 and 4 units) the inputs are more proportional in nature but are still probably separate.

Subject C: I use combined inputs. I do when flying other simulators and I never try to make inputs sequentially - at least not intentionally.

Subject D: My technique is mostly to separate them. During the first maneuvers where I can make a sustained movement I use combined inputs. However, once I get into fine tracking I make separate inputs.

(14) Would you say "cross hairs on the center of the target tail pipe" was the tracking goal?

All subjects: Yes.

(15) How large an error would you accept near termination before initiating a control input: (a) Cross hairs outside tail span? (b) Cross hairs outside tail pipe?

Subject A: Tried to keep cross hairs on tail pipe. This keeps my gain up. If less than tail pipe is accepted at large delays, PIO may not occur.

Subject B: I think that is a function of time delay. For low delays, where the control system was responding crisply, I tried to keep the cross hairs as close to the center of the tail pipe as the visual resolution of the simulator would allow. Any deviation from the center I would try to correct. So, I would say I was operating with a fairly high gain with aggressive-type inputs. For larger time delays, I relaxed my gains and accepted a larger error. Whenever the cross hairs got outside of the tail pipe I would try to correct them back. This was my limit - I relaxed it to this point, but no further.

(16) For this task did target aspect cues influence your control inputs?

Subject A: No aspect cues were used. Scheme is to place the cross hairs on the target and kill drift. Aspect cues are tough to get. The target is not defined by enough TV lines to distinguish aspect very well. Better picture resolution would be a help in killing drift.

Subject B: I really don't think so.

Subject C: I think it affects the problem of determining heading when you're right behind the target. It certainly affects the initial slide over to get in position. In flying a different simulator that used a three-dimensional target model, I had an easier time of sliding over and getting behind the target than I did here. Thus, target aspect cues may be a factor.

Subject D: No. The task I was actually trying to do was put the cross hairs on the tail pipe. The aspect wouldn't have influenced me. I really didn't treat this as a total formation task.

(17) Was motion helpful in performing the tracking task? If yes, in what way?

Subject B: It was helpful in that it provided realism. For example, I noticed some of the body side-force hand-controller coupling previously reported on the orbiter.

Subject C: I'm not sure. I could answer this question better if I had some runs with the motion turned off. Unfortunately, I didn't have any fixed-base runs.

Subject D: I don't know. The fact that I coupled with the stick, it may not have been helpful. The presence of motion is certainly more realistic, so I would probably say yes in that it seems more natural.

(18) Are there any orbiter motion characteristics missing in the simulation? (a) If yes, describe. (b) If yes, would these additional cues have helped in the target tracking task?

Subject C: I don't think you've got the lateral lurch. The orbiter has a peculiar characteristic and it is surprisingly real, as we found out on the first flight. The orbiter cockpit is physically located above the roll axis. Also, the orbiter has a fairly snappy roll response. When a quick roll input is made, the cockpit moves sideways and jerks you sideways on the seat. There is a little of that here, but you're not banged around as in the real vehicle. With this characteristic missing, tracking results should show an improvement.

Subject D: It seemed that the lurch due to roll wasn't quite as pronounced as in other simulations I've flown. This is a very real effect and it is something that was commented on by the crews from the very first flight. If the lurch had been more pronounced in this simulator, then the tracking task would have been more difficult.

(19) Was the visual field of view adequate for the task simulated?

All subjects: Yes.

(20) Was the reticle-horizon-target display adequate for a PIO study?

Subject B: Yes

Subject C: I had a hard time longitudinally interpreting the horizon cue. It didn't jump out and grab me as being obvious what was happening. I don't know if it's moving like a real horizon would, or what; but, somehow the horizon was there and it was always slightly confusing as to what I was really doing.

Subject D: Adequate with one comment. I would recommend flying the sim into a closer distance to the target. I believe the results would better correlate with the orbiter landing task. The closer you get to the target the same vertical displacement subtends a larger error angle. The pilot will stay sensitive to about the same size angle error. Thus, the pilot will tend to be driven toward an unstable situation. In many of the runs I made, I was starting to get into a divergent oscillation just as the run ended. Also, far out the task is more like an angle pointing problem, and as you get closer in it becomes more of a positioning problem. The positioning problem is the one I see in the orbiter. When you get close to the ground you're trying to control attitude, but the thing you're really after is positioning the altitude and trying to get the proper rate of descent.

(21) How do the limitations of the simulator affect the primary task?

Subject A: Resolution of target image is poor - it detracts from one's ability to perform the maneuver. In particular, horizontal translation control would be improved with better resolution.

Subject B: The bulk of the box containing the hand controller prevented one from getting a comfortable position to use the hand controller. I would have preferred to have been seated a littler higher relative to the hand controller; but because of the interference of the box with my knee, I had to accept the vertical position of the seat. Thus, my mechanical transfer to the side stick may have been affected slightly.

Subject C: Mentioned some in comments to other questions.

Subject D: Mentioned some in comments to other questions.

(22) Comment on the workload with and without the side task.

Subject A: When adding the side task, up the pilot rating by 2 units.

Subject B: Adding the side task increased the workload by a Cooper-Harper rating of 1 for each condition across the board. I think the side task definitely indicated when the workloads were high. The first indication of degradation in the control system or an increase in pilot compensation in the primary task was by degradation in side-task performance.

Subjects C and D: Didn't use the side task.

The following questions for mismatched delays were included in the questionnaire given subject B since he was the only subject to experience these conditions. (For roll, τ_r = 4 units (held constant); for pitch, τ_p varied (4, 8, 12, 16, and 20 units); and the audio side task was in use.)

(23) Do PIO tendencies occur at the same or larger values of delay when compared with equal delays in both control channels?

Subject B: Holding roll-channel delay constant at 4 units allowed one to go to higher values in pitch delay by at least 4 units than if matching delays were used. For example, 8 units is where I felt qualitatively that the break was for pitch and roll delays matched. With a mismatch, somewhere around 12 units of delay in pitch is where things started to get pretty bad.

(24) Do PIO tendencies occur only in pitch as time delay τ_p increased?

Subject B: Increasing the workload in pitch does degrade your ability to fly the lateral axis and I noticed some tendency to overcontrol in roll as a result of having to work hard in the pitch axis. However, PIO tendencies occurred only in pitch as time delay τ_p was increased.

(25) Give a Cooper-Harper rating for the following conditions: (a) $\tau_r = 4$, $\tau_p = 4$; (b) $\tau_r = 4$, $\tau_p = 8$; and (c) $\tau_r = 4$, $\tau_p = 16$.

Units of time delay . . .	$\tau_r = 4$ $t_p = 4$	$\tau_r = 4$ $\tau_p = 8$	$\tau_r = 4$ $\tau_p = 16$
Pilot rating	4	5	8

Subject B commented that a rating of 8 indicates that some question of controllability exists for this condition.

APPENDIX D

WORKLOAD ESTABLISHMENT

Two tasks, the visual tracking task and the audio side task, are combined so that in performing the total task the subject is working at his full capacity. This situation must be established for the zero time-delay condition. This assures that the subject has no reserve capability on which to draw when the additional time delays are inserted. In this study the zero time-delay condition is when the simulator is in its normal operating mode with no time delay inserted in the hand-controller pitch- and roll-control input signals. Additional delays are then inserted into the control system. If the presence of these additional delays does not impact the combined task, then pilot performances should not change. If, however, the presence of these additional delays increases the task difficulty, a degradation in performance will occur. A statistical analysis establishes at what particular value of delay this degradation in performance is statistically significant.

For successful application of the side-task technique, it is required that the subject in performing both tasks be fully occupied at the zero time-delay condition. Some effort, therefore, must be made in selecting the proper level of difficulty of the side task. Audio-task difficulty is adjusted by changing the time constant of the first-order unstable system. A number of runs were made with each subject, from which a proper value of instability λ was selected. A complete discussion of this process is given in reference 3 and is omitted here. The final instability values selected for use with the three subjects were as follows:

Audio-task instability setting	
Subject	λ, sec^{-1}
A	1.0
B	1.0
E	2.0

The instability value used for subject E was the same as that used in the studies of references 3 and 4. The larger value of λ was required for this subject because of his familiarity with the audio side task.

Three sets of data are required to show that a subject is operating at his full capacity. These are side-task-only, primary-task-only, and combined-task results. The combined-task and primary-task-only data were obtained with the motion base active. The side-task-only results, however, were obtained under fixed-base conditions. Comparison of the data for the combined task with both the primary-task-only and the side-task-only results is used to show that the subject is operating at his full capacity. These comparisons are given in tables VIII, IX, and X for subjects A, B, and E, respectively. A statistical

test (student's t-test) for the comparison of two sample means was performed for each of the parameters listed. A student's t-value was computed, and significance at either the 5- or 1-percent level was noted.

The results given for subject A in table VIII were limited only to the full 60-sec run. Modification to the program software to obtain two segments of the run was undertaken after completion of subject A's test program. The results show that the significant effects are principally with the side-task variables. This is also the situation with subject E. (See table X.) For these two subjects apparently there is no difference in primary-task variables with and without the side task. Thus, in effect, both subjects accept the visual tracking task as the primary task. In addition, subject E's gain in operating the side task remains nearly the same and indicates that the subject is attacking the side task in the same manner for the combined task as he did for the side-task-only tests. A degradation occurs in $\bar{B}$ and $\bar{\delta}_s$ for the side task when the primary task is added, and this shows that both subjects A and E are fully occupied. If either subject were not fully occupied, his performance on the side task would be more nearly like that of the side task alone. Also, any difference that might occur would not be statistically significant. What is shown, therefore, is what would occur with a pilot fully occupied and with insufficient time to address the side task adequately.

The results for subject B in table IX show statistically significant comparisons for most of the primary-task variables as well as the side-task variables. For the primary task, some degraded tracking-error scores along with reduced control inputs were recorded when the side task was added. Likewise, the side-task parameters $\bar{B}$ and $\bar{\delta}_s$ increased showing poorer side-task performance with an attendant reduction in pilot gain for the combined task. Thus, for the combined task it appears that subject B was operating at his full capacity. The results show that subject B accepted the combined task as a total task rather than dividing his performance on the basis of the primary task and a side task. This is not an uncommon approach since the audio side task demands constant attention for acceptable performance.

The comparisons on tables VIII, IX, and X show that for the combined task all three subjects were operating at their full capacity at the zero time-delay condition. This establishes the basis against which degradations can be judged due to the addition of time delays in the control system.

APPENDIX E

ANALYSIS OF TRACKING PERFORMANCE

USING ONE-WAY ANOV

All tracking runs in this study were of 60-sec duration. During the run the target was driven in altitude by a cosine wave of very low frequency through one-half cycle of motion. In addition, range to the target was varied linearly with time from 182.88 m (600 ft) at the initiation of the run to 91.44 m (300 ft) at the termination of the run. Because tracking performance may vary during the run due to these two factors, the data have been examined during the first half and the last half of the run, as well as for the total run.

A one-way analysis of variance (ANOV) for time delay was performed on each of the measured variables for which an rms value was computed. Significance was then established at the 5-percent level. Summary tables, one for each subject, denoting significance only are given as tables XI to XV. These tables provide a condensed version of the numerical results. From an examination of these tables the following observations can be made:

(1) The effect of time delay was insignificant on $\bar{\varepsilon}_v$ (vertical displacement between target and orbiter) for the different time segments of the runs for the different subjects. (Note the single exception for subject B for the first 30-sec segment.)

(2) The effect of time delay was found to be significant on elevation line-of-sight angle $\bar{\eta}$ for the total 60-sec run for all subjects. (For subject E the effect was significant only during the last half of the run; and for subject D, only during the first half of the run. For subjects B and C the effect was significant for all run segments.)

(3) Lateral displacements $\bar{\varepsilon}_h$ and azimuth line-of-sight angles $\bar{\xi}$ for the first 30 sec of run time (primarily target acquisition) show insignificant effects of time delay.

(4) With one exception ($\bar{\xi}$ for subject E) the data for lateral displacements and azimuth line-of-sight angles for the last 30 sec of run time show that the effect of time delay is significant for the four subjects for which data were available.

(5) The effect of time delay is significant on some of the pitch- and roll-control input data for tracking following target acquisition (second 30-sec interval results for $\bar{\delta}_a$ and total 60-sec results for $\bar{\delta}_e$). The results for a given control, however, are not consistent across subjects. With the exception of the results for subject E (simulation engineer) with no side task, data for at least one control showed a significant time-delay effect for each different test combination examined.

Of the various results that have been itemized, most appear as expected. For example, the fact that lateral target acquisition (item (3)) shows no

effect of time delay seems reasonable since there were no constraints on achieving initial alinement. Items (2), (4), and (5) likewise are as expected since similar results were obtained in previous studies. Only item (1) is of particular concern since it differs from the results of references 1 to 4 that indicate a significant time-delay effect on $\bar{\varepsilon}_v$. From an analysis of the task plus some additional runs performed after the completion of this test program, the following two task differences were believed responsible for the results:

(a) Only one-half cycle of target motion was employed herein as compared to at least 4 cycles of motion in the references.

(b) Range decreased between target and orbiter during the run for the test herein, whereas the range remained constant at 182.88 m (600 ft) in the references.

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TABLE I.- PARAMETER VALUES AND PHYSICAL CHARACTERISTICS

USED IN SIMULATION

Longitudinal aerodynamic characteristics		
Normal	Axial	Pitch
$C_{Z,0} = -0.2291$	$C_{X,0} = 0$	$C_{m,0} = 0$
$C_{Z_\alpha} = -3.4490$	$C_{X_\alpha} = 0.3384$	$C_{m_\alpha} = -0.0253$
$C_{Z_q} = -17.5013$		$C_{m_q} = -16.4431$
$C_{Z_{\delta e}} = 0.5744$		$C_{m_{\delta e}} = 0.2922$
Lateral aerodynamic characteristics		
Roll	Yaw	Side force
$C_{l_\beta} = 0.1518$	$C_{n_\beta} = 0.8309$	$C_{Y_\beta} = -4.8484$
$C_{l_r} = 0.1070$	$C_{n_r} = -1.3931$	
$C_{l_p} = -0.3422$	$C_{n_p} = 0.2717$	$C_{Y_p} = 0.1323$
$C_{l_{\delta a}} = 0.0265$	$C_{n_{\delta a}} = 0.0004$	$C_{Y_{\delta a}} = -0.0292$
Physical characteristics		

I_X = 1 169 237.058 kg-m^2 (862 385 slug-ft^2)

I_Y = 8 729 397.232 kg-m^2 (6 438 473 slug-ft^2)

I_Z = 8 991 771.053 kg-m^2 (6 631 990 slug-ft^2)

I_{XZ} = -218 614.797 kg-m^2 (-161 242 slug-ft^2)

W = 817 761.0617 N (183 840 lb)

S = 249.9092 m^2 (2690 ft^2)

b = 23.7917 m (78.0567 ft)

$\bar{c}$ = 12.0602 m (39.5675 ft)

TABLE II.- TWO-WAY ANALYSIS OF VARIANCE FOR TIME

DELAYS AND SUBJECTS WITH NO SIDE TASK

(a) rms elevation angle

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	4	16	125
$F_{critical}$	2.44	2.44	1.72	---
F	[a]22.31	[a]10.38	[a]2.50	---

(b) rms azimuth angle

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	3	12	100
$F_{critical}$	2.46	2.70	1.85	---
F	[a]18.06	0.89	1.18	---

(c) rms pitch-control inputs

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	4	16	125
$F_{critical}$	2.44	2.44	1.72	---
F	[a]9.87	[a]5.78	0.76	---

(d) rms roll control inputs

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	4	16	125
$F_{critical}$	2.44	2.44	1.72	---
F	[a]30.55	[a]28.92	[a]2.87	---

[a]Statistical significance at the 5-percent level.

TABLE III.- MEANS, STANDARD DEVIATIONS, AND t STATISTICS FOR rms DATA OBTAINED AT VARIOUS TIME DELAYS WITH NO SIDE TASK

[Azimuth-angle results for last 30 sec of run]

(a) Subject A

Parameter	Added time delay, msec				
	0	125	250	375	500
$\eta \times 10^2$:					
Mean . . .	0.753	0.737	0.968	1.093	1.336
s	0.233	0.189	0.247	0.213	0.366
t	Control	0.102	1.454	[a]2.296	[a]3.930
$\xi \times 10^2$:					
Mean . . .	-------	-----	------	------	------
s	-------	-----	------	------	------
t	Control	-----	------	------	------
$\delta_e \times 10^2$:					
Mean . . .	0.854	1.177	1.662	1.985	1.899
s	0.108	0.425	0.932	1.035	1.415
t	Control	0.615	1.540	[a]2.156	[a]2.224
$\delta_a \times 10^2$:					
Mean . . .	2.407	3.704	5.562	6.540	6.480
s	0.492	1.346	2.353	2.493	2.667
t	Control	1.098	[a]2.672	[a]3.501	[a]3.449

(b) Subject B

Parameter	Added time delay, msec				
	0	125	250	375	500
$\eta \times 10^2$:					
Mean . . .	0.351	0.420	0.558	0.891	1.057
s	0.093	0.142	0.181	0.326	0.304
t	Control	0.529	1.575	[a]4.101	[a]5.363
$\xi \times 10^2$:					
Mean . . .	0.359	0.394	0.702	1.468	0.949
s	0.096	0.169	0.307	0.722	0.174
t	Control	0.160	1.683	[a]5.191	[a]2.762
$\delta_e \times 10^2$:					
Mean . . .	0.889	1.121	1.497	2.167	1.873
s	0.150	0.250	0.699	0.966	1.037
t	Control	0.558	1.464	[a]3.076	[a]2.369
$\delta_a \times 10^2$:					
Mean . . .	4.398	5.081	7.270	9.892	11.529
s	0.842	0.998	1.557	1.003	2.569
t	Control	0.771	[a]3.246	[a]6.210	[a]8.061

[a]Statistical significance at the 5-percent level.

TABLE III.- Continued

(c) Subject C

Parameter	Added time delay, msec				
	0	125	250	375	500
$\eta \times 10^2$:					
Mean . . .	0.385	0.488	0.634	0.976	1.248
s	0.108	0.177	0.242	0.432	0.532
t	Control	0.530	1.276	[a]3.028	[a]4.425
$\xi \times 10^2$:					
Mean . . .	0.563	0.629	0.685	1.220	1.647
s	0.566	0.170	0.132	0.383	0.881
t	Control	0.255	0.473	[a]2.553	[a]4.215
$\delta_e \times 10^2$:					
Mean . . .	1.129	1.126	1.704	1.994	1.771
s	0.209	0.270	0.628	0.806	0.269
t	Control	0.303	2.010	[a]3.023	[a]2.246
$\delta_a \times 10^2$:					
Mean . . .	4.803	7.666	9.637	11.486	13.108
s	0.443	0.852	3.986	3.539	4.028
t	Control	1.643	[a]2.774	[a]3.835	[a]4.765

(d) Subject D

Parameter	Added time delay, msec				
	0	125	250	375	500
$\eta \times 10^2$:					
Mean . . .	0.465	0.658	0.644	0.749	0.882
s	0.091	0.187	0.109	0.235	0.285
t	Control	1.707	1.581	[a]2.516	[a]3.691
$\xi \times 10^2$:					
Mean . . .	0.459	0.569	0.674	1.411	1.024
s	0.055	0.259	0.234	0.677	0.375
t	Control	0.502	0.480	[a]4.335	[a]2.572
$\delta_e \times 10^2$:					
Mean . . .	0.686	0.932	0.956	1.101	1.033
s	0.039	0.113	0.148	0.244	0.054
t	Control	[a]2.769	[a]3.035	[a]4.670	[a]3.903
$\delta_a \times 10^2$:					
Mean . . .	5.512	6.833	7.245	7.859	7.912
s	0.783	0.951	1.023	0.700	1.786
t	Control	1.869	[a]2.452	[a]3.321	[a]3.396

[a]Statistical significance at the 5-percent level.

TABLE III.- Concluded

(e) Subject E

Parameter	Added time delay, msec				
	0	125	250	375	500
$\eta \times 10^2$:					
Mean . . .	0.513	0.550	0.604	0.644	0.780
s	0.082	0.115	0.222	0.097	0.219
t	Control	0.402	0.989	1.420	[a]2.906
$\xi \times 10^2$:					
Mean . . .	0.556	0.550	0.752	1.032	1.115
s	0.189	0.237	0.418	0.738	0.489
t	Control	0.020	0.741	1.802	[a]2.113
$\delta_e \times 10^2$:					
Mean . . .	1.293	1.304	1.411	1.471	1.668
s	0.140	0.251	0.193	0.245	0.329
t	Control	0.078	0.847	1.277	[a]2.697
$\delta_a \times 10^2$:					
Mean . . .	4.649	4.626	5.273	5.118	5.969
s	0.415	0.930	0.576	1.493	0.778
t	Control	0.044	1.178	0.887	[a]2.495

[a]Statistical significance at the 5-percent level.

TABLE IV.- DUNCAN MULTIPLE-RANGE TESTS FOR SUBJECT EFFECTS WITH NO SIDE TASK

Time delay, msec		rms elevation angle	rms pitch-control inputs	rms roll-control inputs
τ = 0	d.o.f.	25	25	25
	L.S.R.	0.2142, 0.2253, 0.2319, 0.2371	0.2425, 0.2551, 0.2626, 0.2634	0.7171, 0.7540, 0.7761, 0.7933
	Difference in subject's means	(A - E) = [a]0.2392, (E - D) = 0.0486 (D - C) = 0.0798, (C - B) = 0.0344 (A - D) = [a]0.2878, (E - C) = 0.1284 (D - B) = 0.1142, (A - C) = [a]0.3676 (E - B) = 0.1682, (A - B) = [a]0.4020	(E - C) = 0.1638, (C - B) = 0.2401 (B - A) = 0.0356, (A - D) = 0.1675 (E - B) = [a]0.4039, (C - A) = [a]0.2757 (B - D) = 0.2031, (E - A) = [a]0.4395 (C - D) = [a]0.2757, (E - D) = [a]0.6020	(D - C) = 0.7091, (C - E) = 0.1544 (E - B) = 0.2506, (B - A) = [a]1.9914 (D - E) = [a]0.8635, (C - B) = 0.4050 (E - A) = [a]2.2420, (D - B) = [a]1.1141 (C - A) = [a]2.3964, (D - A) = [a]3.1055
τ = 125	d.o.f.	25	25	25
	L.S.R.	0.1963, 0.2063, 0.2124, 0.2171	0.4254, 0.4473, 0.4604, 0.4706	1.2066, 1.2685, 1.3057, 1.3346
	Difference in subject's means	(A - D) = 0.0796, (D - E) = 0.1076 (E - C) = 0.0619, (C - B) = 0.0682 (A - E) = 0.1872, (D - C) = 0.1695 (E - B) = 0.1301, (A - C) = [a]0.2491 (D - B) = [a]0.2377, (A - B) = [a]0.3173	(E - A) = 0.1274, (A - C) = 0.0505 (C - B) = 0.0050, (B - D) = 0.1887 (E - C) = 0.1739, (A - B) = 0.0555 (C - D) = 0.1937, (E - B) = 0.1829 (A - D) = 0.2442, (E - D) = 0.3716	(C - D) = 0.8333, (D - B) = [a]1.7524 (B - E) = 0.4548, (E - A) = 0.9222 (C - B) = [a]2.5857, (D - E) = [a]2.2072 (B - A) = [a]1.3770, (C - E) = [a]3.0405 (D - A) = [a]3.1294, (C - A) = [a]5.0806
τ = 250	d.o.f.	25	25	25
	L.S.R.	0.2463, 0.2588, 0.2664, 0.2723	0.8733, 0.9182, 0.9452, 0.9661	2.6663, 2.8032, 2.8854, 2.9493
	Difference in subject's means	(A - D) = [a]0.3247, (D - C) = 0.0097 (C - E) = 0.0296, (E - B) = 0.0463 (A - B) = [a]0.4103, (A - C) = [a]0.3344 (D - E) = 0.0393, (C - B) = 0.0759 (A - E) = [a]0.3640, (D - B) = 0.0856	No comparisons significant at the 5-percent level	(C - B) = 2.3669, (B - D) = 0.0257 (D - A) = 1.6826, (A - E) = 0.2894 (C - D) = 2.3926, (B - A) = 1.7083 (D - E) = 1.9720, (C - A) = [a]4.0752 (B - E) = 1.9977, (C - E) = [a]4.3646
τ = 375	d.o.f.	25	25	25
	L.S.R.	0.3381, 0.3555, 0.3659, 0.3740	1.1503, 1.2093, 1.2447, 1.2723	2.5216, 2.6509, 2.7287, 2.7891
	Difference in subject's means	(A - C) = 0.1175, (C - B) = 0.0851 (B - D) = 0.1413, (D - E) = 0.1055 (A - B) = 0.2026, (C - D) = 0.2264 (B - E) = 0.2468, (A - D) = 0.3439 (C - E) = 0.3319, (A - E) = [a]0.4494	No comparisons significant at the 5-percent level	(C - B) = 1.5941, (B - D) = 2.0331 (D - A) = 1.3183, (A - E) = 1.4221 (C - D) = [a]3.6272, (B - A) = [a]3.3514 (D - E) = [a]2.7040, (C - A) = [a]4.9455 (B - E) = [a]4.7755, (C - E)= [a]6.3676
τ = 500	d.o.f.	25	25	25
	L.S.R.	0.4259, 0.4479, 0.4610, 0.4713	1.0184, 1.0708, 1.1022, 1.1266	3.0670, 3.2244, 3.3189, 3.3925
	Difference in subject's means	(A - C) = 0.0875, (C - B) = 0.1914 (B - D) = 0.1747, (D - E) = 0.1017 (A - B) = 0.2789, (C - D) = 0.3661 (B - E) = 0.2764, (A - D) = 0.4536 (C - E) = [a]0.4678, (A - E) = [a]0.5553	No comparisons significant at the 5-percent level	(C - B) = 1.5790, (B - D) = [a]3.6177 (D - A) = 1.4318, (A - E) = 0.5105 (C - D) = [a]5.1967, (B - A) = [a]5.0495 (D - E) = 1.9423, (C - A) = 6.6285 (B - E) = [a]5.5600, (C - E) = [a]7.1390

[a]Statistical significance at the 5-percent level.

TABLE V.- TWO-WAY ANALYSIS OF VARIANCE FOR TIME DELAYS AND SUBJECTS WITH SIDE TASK

(a) rms elevation angle

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	2	8	75
$F_{critical}$	2.49	3.12	2.06	---
F	[a]27.73	[a]34.96	[a]4.27	---

(b) rms azimuth angle

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	1	4	50
$F_{critical}$	2.56	4.03	2.56	---
F	[a]14.63	0.46	0.32	---

(c) rms pitch-control inputs

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	2	8	75
$F_{critical}$	2.49	3.12	2.06	---
F	[a]16.30	[a]13.03	[a]3.24	---

[a]Statistical significance at the 5-percent level.

TABLE V.- Concluded

(d) rms roll-control inputs

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	2	8	75
$F_{critical}$	2.49	3.12	2.06	---
F	[a]29.59	1.19	[a]6.44	---

(e) rms tone error

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	2	8	75
$F_{critical}$	2.49	3.12	2.06	---
F	[a]9.64	[a]44.05	1.31	---

(f) rms thumb-wheel deflection

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	2	8	75
$F_{critical}$	2.49	3.12	2.06	---
F	[a]5.67	[a]22.90	1.08	---

(g) Pilot gain, K_*

Experimental factor	Time delay	Subject	Delay/subject interaction	Error
Degrees of freedom . . .	4	2	8	75
$F_{critical}$	2.49	3.12	2.06	---
F	[a]5.49	[a]993.82	1.31	---

[a]Statistical significance at the 5-percent level.

TABLE VI.- MEANS, STANDARD DEVIATIONS, AND t STATISTICS FOR rms DATA OBTAINED AT VARIOUS TIME DELAYS WITH SIDE TASK

[Azimuth-angle results for last 30 sec of run]

(a) Subject A

Parameter	Added time delay, msec				
	0	125	250	375	500
$\eta \times 10^2$:					
Mean	0.763	0.763	0.797	1.242	2.034
s	0.158	0.146	0.244	0.230	0.763
t	Control	0.001	0.153	[a]2.157	[a]5.721
$\xi \times 10^2$:					
Mean	-------	-----	-----	------	------
s	-------	-----	-----	------	------
t	-------	-----	-----	------	------
$\delta_e \times 10^2$:					
Mean	0.968	1.278	1.761	2.128	3.583
s	0.154	0.431	0.660	1.360	1.358
t	Control	0.576	1.473	[a]2.157	[a]4.863
$\delta_a \times 10^2$:					
Mean	2.530	3.155	4.411	4.521	11.187
s	0.604	0.612	1.763	2.426	4.178
t	Control	0.464	1.397	1.479	[a]6.430
Tone error, B:					
Mean	0.706	0.748	0.749	0.836	1.021
s	0.148	0.199	0.197	0.229	0.103
t	Control	0.403	0.413	1.252	[a]3.022
Thumb-wheel deflection, δ_s:					
Mean	0.732	0.784	0.724	0.793	0.830
s	0.181	0.241	0.133	0.124	0.119
t	Control	0.542	0.090	0.630	1.021
Pilot gain, K_*:					
Mean	1.031	1.070	0.986	0.980	0.813
s	0.073	0.140	0.098	0.155	0.124
t	Control	0.554	0.642	0.732	[a]3.107

[a]Statistical significance at the 5-percent level.

TABLE VI.- Continued

(b) Subject B

Parameter	Added time delay, msec				
	0	125	250	375	500
$\eta \times 10^2$:					
Mean	0.397	0.482	0.657	0.829	1.016
s	0.092	0.128	0.238	0.208	0.201
t	Control	0.807	[a]2.481	[a]4.120	[a]5.896
$\xi \times 10^2$:					
Mean	0.404	0.570	0.788	1.028	1.716
s	0.117	0.191	0.195	0.422	0.534
t	Control	0.868	2.005	[a]3.253	[a]6.895
$\delta_e \times 10^2$:					
Mean	0.566	0.646	1.056	1.670	1.956
s	0.054	0.138	0.249	0.436	0.699
t	Control	0.355	[a]2.174	[a]4.897	[a]6.164
$\delta_a \times 10^2$:					
Mean	2.678	3.374	4.402	6.795	9.509
s	0.581	1.111	1.559	1.589	2.346
t	Control	0.777	1.926	[a]4.597	[a]7.627
Tone error, B:					
Mean	0.474	0.513	0.671	0.789	0.895
s	0.162	0.168	0.236	0.219	0.113
t	Control	0.367	1.851	[a]2.953	[a]3.953
Thumb-wheel deflection, δ_s:					
Mean.	0.555	0.587	0.682	0.801	0.878
s	0.158	0.163	0.194	0.148	0.105
t	Control	0.358	1.415	[a]2.733	[a]3.587
Pilot gain, K_*:					
Mean	1.189	1.179	1.053	1.043	0.987
s	0.089	0.132	0.143	0.121	0.107
t	Control	0.155	1.973	[a]2.120	[a]2.933

[a]Statistical significance at the 5-percent level.

TABLE VI.- Concluded

(c) Subject E

Parameter	Added time delay, msec				
	0	125	250	375	500
$\eta \times 10^2$:					
Mean	0.500	0.453	0.607	0.590	0.907
s	0.102	0.084	0.123	0.119	0.182
t	Control	0.640	1.461	1.235	[a]5.561
$\xi \times 10^2$:					
Mean	0.699	0.668	1.027	1.170	1.237
s	0.144	0.241	0.400	0.457	0.329
t	Control	0.163	1.700	[a]2.444	[a]2.794
$\delta_e \times 10^2$:					
Mean	1.300	1.102	1.334	1.321	1.589
s	0.108	0.136	0.210	0.180	0.200
t	Control	2.002	0.339	0.206	[a]2.911
$\delta_a \times 10^2$:					
Mean	4.799	4.180	4.669	4.511	5.334
s	0.595	0.760	0.762	0.770	1.096
t	Control	1.320	0.277	0.614	1.139
Tone error, B:					
Mean	0.353	0.378	0.480	0.406	0.511
s	0.088	0.145	0.095	0.073	0.104
t	Control	0.424	2.020	0.887	[a]2.646
Thumb-wheel deflection, δ_s:					
Mean.	0.844	0.882	1.081	0.991	1.180
s	0.120	0.312	0.198	0.126	0.191
t	Control	0.324	2.033	1.258	[a]2.880
Pilot gain, K_*:					
Mean	2.438	2.366	2.607	2.464	2.326
s	0.327	0.136	0.067	0.184	0.149
t	Control	0.647	1.522	0.239	1.006

[a]Statistical significance at the 5-percent level.

TABLE VII.- DUNCAN MULTIPLE-RANGE TESTS FOR SUBJECT EFFECTS FOR

SUBJECTS A, B, AND E WITH AUDIO SIDE TASK

Time delay, msec		rms elevation angle	rms pitch inputs	rms tone error	rms thumb-wheel deflection	rms pilot gain, $\bar{K}_*$
τ = 0	d.o.f.	15	15	15	15	15
	L.S.R.	0.1486, 0.1561	0.1390, 0.1460	0.1678, 0.1763	0.1904, 0.2000	0.2460, 0.2582
	Difference in subject's means	(A - E) = [a]0.2630 (E - B) = 0.1030 (A - B) = [a]0.3660	(E - A) = [a]0.3320 (A - B) = [a]0.4019 (E - B) = [a]0.7339	(A - B) = [a]0.2322 (B - E) = 0.1208 (A - E) = [a]0.3531	(E - A) = 0.1118 (A - B) = 0.1774 (E - B) = [a]0.2892	(E - B) = [a]1.2479 (B - A) = 0.1586 (E - A) = [a]1.4068
τ = 125	d.o.f.	15	15	15	15	15
	L.S.R.	0.1502, 0.1577	0.3353, 0.3520	0.2115, 0.2221	0.3027, 0.3176	0.1667, 0.1751
	Difference in subject's means	(A - B) = [a]0.[illegible]811 (B - E) = 0.0284 (A - E) = [a]0.3095	(A - E) = 0.1760 (E - B) = [a]0.4557 (A - B) = [a]0.6317	(A - B) = [a]0.2351 (B - E) = 0.1347 (A - E) = [a]0.3698	(E - A) = 0.0976 (A - B) = 0.1971 (E - B) = 0.2947	(E - B) = [a]1.1866 (B - A) = 0.1091 (E - A) = [a]1.2957
τ = 250	d.o.f.	15	15	15	15	15
	L.S.R.	0.2570, 0.2699	0.5222, 0.5483	0.2285, 0.2398	0.2182, 0.2291	0.1315, 0.1381
	Difference in subject's means	(A - B) = 0.1396 (B - E) = 0.0505 (A - E) = 0.1901	(A - E) = 0.4266 (E - B) = 0.2774 (A - B) = [a]0.7040	(A - B) = 0.0778 (B - E) = 0.1914 (A - E) = [a]0.2692	(E - A) = [a]0.3573 (A - B) = 0.0412 (E - B) = [a]0.3985	(E - B) = [a]1.5538 (B - A) = 0.0671 (E - A) = [a]1.6210
τ = 375	d.o.f.	15	15	15	15	15
	L.S.R.	0.2363, 0.2481	1.0213, 1.0722	0.2307, 0.2421	0.1639, 0.1719	0.1914, 0.2010
	Difference in subject's means	(A - B) = [a]0.4129 (B - E) = [a]0.2389 (A - E) = [a]0.6518	(A - B) = 0.4579 (B - E) = 0.3496 (A - E) = 0.8075	(A - B) = 0.0478 (B - E) = [a]0.3829 (A - E) = [a]0.4307	(E - B) = [a]0.1892 (B - A) = 0.0086 (E - A) = [a]0.1978	(E - B) [a]1.4212 (B - A) = 0.0632 (E - A) = [a]1.4844
τ = 500	d.o.f.	15	15	15	15	15
	L.S.R.	0.5743, 0.6029	1.0927, 1.1471	0.1309, 0.1375	0.1764, 0.1852	0.1569, 0.1646
	Difference in subject's means	(A - B) = [a]1.0181 (B - E) = 0.1090 (A - E) = [a]1.1271	(A - B) = [a]1.6278 (B - E) = 0.3671 (A - E) = [a]1.9949	(A - B) = 0.1249 (B - E) = [a]0.3842 (A - E) = [a]0.5101	(E - B) = [a]0.3012 (B - A) = 0.0481 (E - A) = [a]0.3493	(E - B) = [a]1.3389 (B - A) = 0.1734 (E - A) = [a]1.5123

[a]Statistical significance at the 5-percent level.

TABLE VIII.- WORKLOAD SUMMARY FOR SUBJECT A

FOR ZERO ADDED TIME DELAY

$[\tau_r = \tau_p = 0]$

Objective	Parameter	Run segment		
		First 30 sec	Last 30 sec	Total 60 sec
Comparison of primary task only with combined task	$\bar{\varepsilon}_v$	NA	NA	(*)
	$\bar{\varepsilon}_h$	NA	NA	No data
	$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	NA	NA	No data
	$\bar{\delta}_e$	NA	NA	-------
	$\bar{\delta}_a$	NA	NA	-------
	$\bar{\eta}$	NA	NA	-------
	$\bar{\xi}$	NA	NA	-------
Comparison of side task only with combined task	$\bar{B}$	NA	NA	(**)
	$\bar{\delta}_s$	NA	NA	(**)
	$\bar{K}_*$	NA	NA	(**)
Replicates each data set				6

*Significant at the 5-percent level.
**Significant at the 1-percent level.
---Not significant.
NANot available.

TABLE IX.- WORKLOAD SUMMARY FOR SUBJECT B

FOR ZERO ADDED TIME DELAY

$[\tau_r = \tau_p = 0]$

Objective	Parameter	Run segment		
		First 30 sec	Last 30 sec	Total 60 sec
Comparison of primary task only with combined task	$\bar{\varepsilon}_v$	----	(*)	----
	$\bar{\varepsilon}_h$	(**)	----	(**)
	$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	(**)	(**)	(**)
	$\bar{\delta}_e$	(**)	(**)	(**)
	$\bar{\delta}_a$	(**)	(*)	(**)
	$\bar{\eta}$	----	----	----
	$\bar{\xi}$	(**)	----	(**)
Comparison of side task only with combined task	$\bar{B}$	(*)	(**)	(**)
	$\bar{\delta}_s$	(**)	(**)	(**)
	$\bar{K}_*$	----	(**)	(*)
Replicates each data set		6	6	6

*Significant at the 5-percent level.
**Significant at the 1-percent level.
---Not significant.

TABLE X.- WORKLOAD SUMMARY FOR SUBJECT E

FOR ZERO ADDED TIME DELAY

$[\tau_r = \tau_p = 0]$

Objective	Parameter	Run segment		
		First 30 sec	Last 30 sec	Total 60 sec
Comparison of primary task only with combined task	$\bar{\varepsilon}_v$	----	----	----
	$\bar{\varepsilon}_h$	----	----	----
	$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	----	----	----
	$\bar{\delta}_e$	----	----	----
	$\bar{\delta}_a$	----	----	----
	$\bar{\eta}$	----	(*)	----
	$\bar{\xi}$	----	----	----
Comparison of side task only with combined task	$\bar{B}$	(**)	(**)	(**)
	$\bar{\delta}_s$	(**)	(**)	(**)
	$\bar{K}_*$	----	----	----
Replicates each data set		6	6	6

*Significant at the 5-percent level.
**Significant at the 1-percent level.
---Not significant.

TABLE XI.- SUMMARY OF RESULTS OF ONE-WAY ANALYSIS OF VARIANCE FOR TIME DELAYS FOR SUBJECT A

(a) No side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{\varepsilon}_v$	NA	NA	---
$\bar{\varepsilon}_h$	NA	NA	NA
$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	NA	NA	NA
$\bar{\delta}_e$	NA	NA	---
$\bar{\delta}_a$	NA	NA	(*)
$\bar{\eta}$	NA	NA	(*)
$\bar{\xi}$	NA	NA	---

(b) With side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{\varepsilon}_v$	NA	NA	---
$\bar{\varepsilon}_h$	NA	NA	NA
$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	NA	NA	NA
$\bar{\delta}_e$	NA	NA	(*)
$\bar{\delta}_a$	NA	NA	(*)
$\bar{\eta}$	NA	NA	(*)
$\bar{\xi}$	NA	NA	---
$\bar{B}$	NA	NA	(*)
$\bar{\delta}_s$	NA	NA	---
$\bar{K}_*$	NA	NA	---

*Significant effect of time delay at the 5-percent level.

---Not significant.

NANot available.

TABLE XII.- SUMMARY OF RESULTS OF ONE-WAY ANALYSIS OF VARIANCE FOR TIME DELAYS FOR SUBJECT B

(a) No side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{\varepsilon}_v$	(*)	---	---
$\bar{\varepsilon}_h$	---	(*)	---
$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	(*)	(*)	---
$\bar{\delta}_e$	---	(*)	(*)
$\bar{\delta}_a$	(*)	(*)	(*)
$\bar{\eta}$	(*)	(*)	(*)
$\bar{\xi}$	---	(*)	---

(b) With side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{\varepsilon}_v$	---	---	---
$\bar{\varepsilon}_h$	---	(*)	---
$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	---	(*)	---
$\bar{\delta}_e$	(*)	(*)	(*)
$\bar{\delta}_a$	(*)	(*)	(*)
$\bar{\eta}$	(*)	(*)	(*)
$\bar{\xi}$	---	(*)	---
$\bar{B}$	---	(*)	(*)
$\bar{\delta}_s$	---	(*)	(*)
$\bar{K}_*$	---	(*)	(*)

*Significant effect of time delay at the 5-percent level.
---Not significant.
NANot available.

TABLE XIII.- SUMMARY OF RESULTS OF ONE-WAY ANALYSIS OF VARIANCE FOR TIME DELAYS FOR SUBJECT C

(a) No side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{\varepsilon}_v$	---	---	---
$\bar{\varepsilon}_h$	---	(*)	---
$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	---	(*)	---
$\bar{\delta}_e$	---	(*)	(*)
$\bar{\delta}_a$	(*)	(*)	(*)
$\bar{\eta}$	(*)	(*)	(*)
$\bar{\xi}$	---	(*)	---

(b) With side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{\varepsilon}_v$	NA	NA	NA
$\bar{\varepsilon}_h$	NA	NA	NA
$\bar{\varepsilon}_v + \bar{\varepsilon}_h$	NA	NA	NA
$\bar{\delta}_e$	NA	NA	NA
$\bar{\delta}_a$	NA	NA	NA
$\bar{\eta}$	NA	NA	NA
$\bar{\xi}$	NA	NA	NA
$\bar{B}$	NA	NA	NA
$\bar{\delta}_s$	NA	NA	NA
$\bar{K}_*$	NA	NA	NA

*Significant effect of time delay at the 5-percent level.
---Not significant.
NANot available.

TABLE XIV.- SUMMARY OF RESULTS OF ONE-WAY ANALYSIS OF VARIANCE FOR TIME DELAYS FOR SUBJECT D

(a) No side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{\epsilon}_v$	---	---	---
$\bar{\epsilon}_h$	---	(*)	---
$\bar{\epsilon}_v + \bar{\epsilon}_h$	---	(*)	---
$\bar{\delta}_e$	(*)	(*)	(*)
$\bar{\delta}_a$	---	---	(*)
$\bar{\eta}$	(*)	---	(*)
$\bar{\xi}$	---	(*)	---

(b) With side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{\epsilon}_v$	NA	NA	NA
$\bar{\epsilon}_h$	NA	NA	NA
$\bar{\epsilon}_v + \bar{\epsilon}_h$	NA	NA	NA
$\bar{\delta}_e$	NA	NA	NA
$\bar{\delta}_a$	NA	NA	NA
$\bar{\eta}$	NA	NA	NA
$\bar{\xi}$	NA	NA	NA
$\bar{B}$	NA	NA	NA
$\bar{\delta}_s$	NA	NA	NA
$\bar{K}_*$	NA	NA	NA

*Significant effect of time delay at the 5-percent level.
---Not significant.
NANot available.

TABLE XV.- SUMMARY OF RESULTS OF ONE-WAY ANALYSIS OF VARIANCE FOR TIME DELAYS FOR SUBJECT E

(a) No side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{e}_v$	---	---	---
$\bar{\epsilon}_h$	---	(*)	---
$\bar{\epsilon}_v + \bar{\epsilon}_h$	---	(*)	---
$\bar{\delta}_e$	---	---	---
$\bar{\delta}_a$	---	---	---
$\bar{\eta}$	---	(*)	(*)
$\bar{\xi}$	---	---	---

(b) With side task

Parameter	First 30 sec	Second 30 sec	Total 60 sec
$\bar{e}_v$	---	---	---
$\bar{\epsilon}_h$	---	(*)	(*)
$\bar{\epsilon}_v + \bar{\epsilon}_h$	(*)	(*)	(*)
$\bar{\delta}_e$	(*)	(*)	(*)
$\bar{\delta}_a$	---	---	---
$\bar{\eta}$	---	(*)	(*)
$\bar{\xi}$	---	(*)	(*)
$\bar{B}$	(*)	(*)	(*)
$\bar{\delta}_s$	---	(*)	(*)
$\bar{K}_*$	---	---	(*)

*Significant effect of time delay at the 5-percent level.
---Not significant.
NANot available.

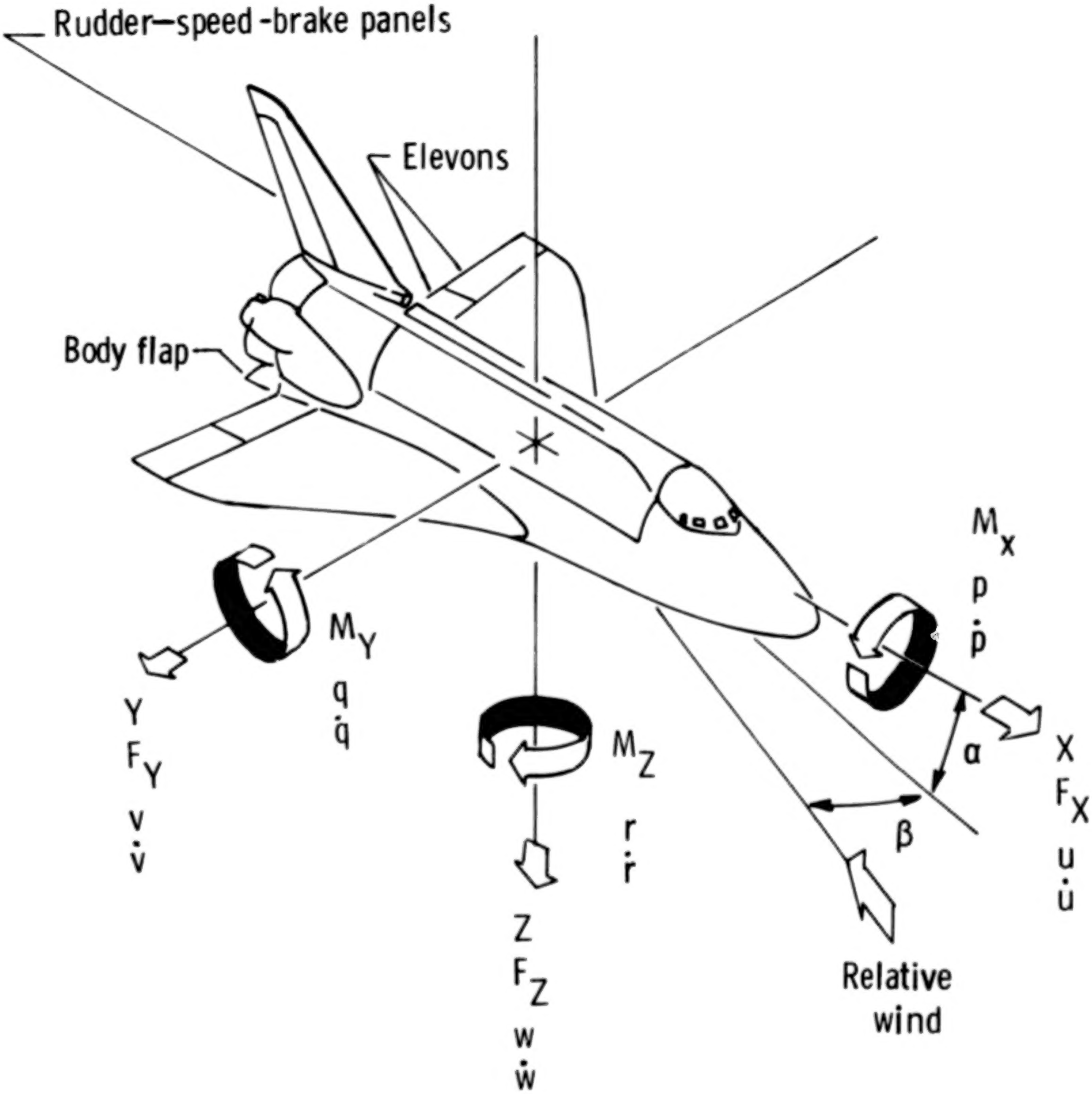
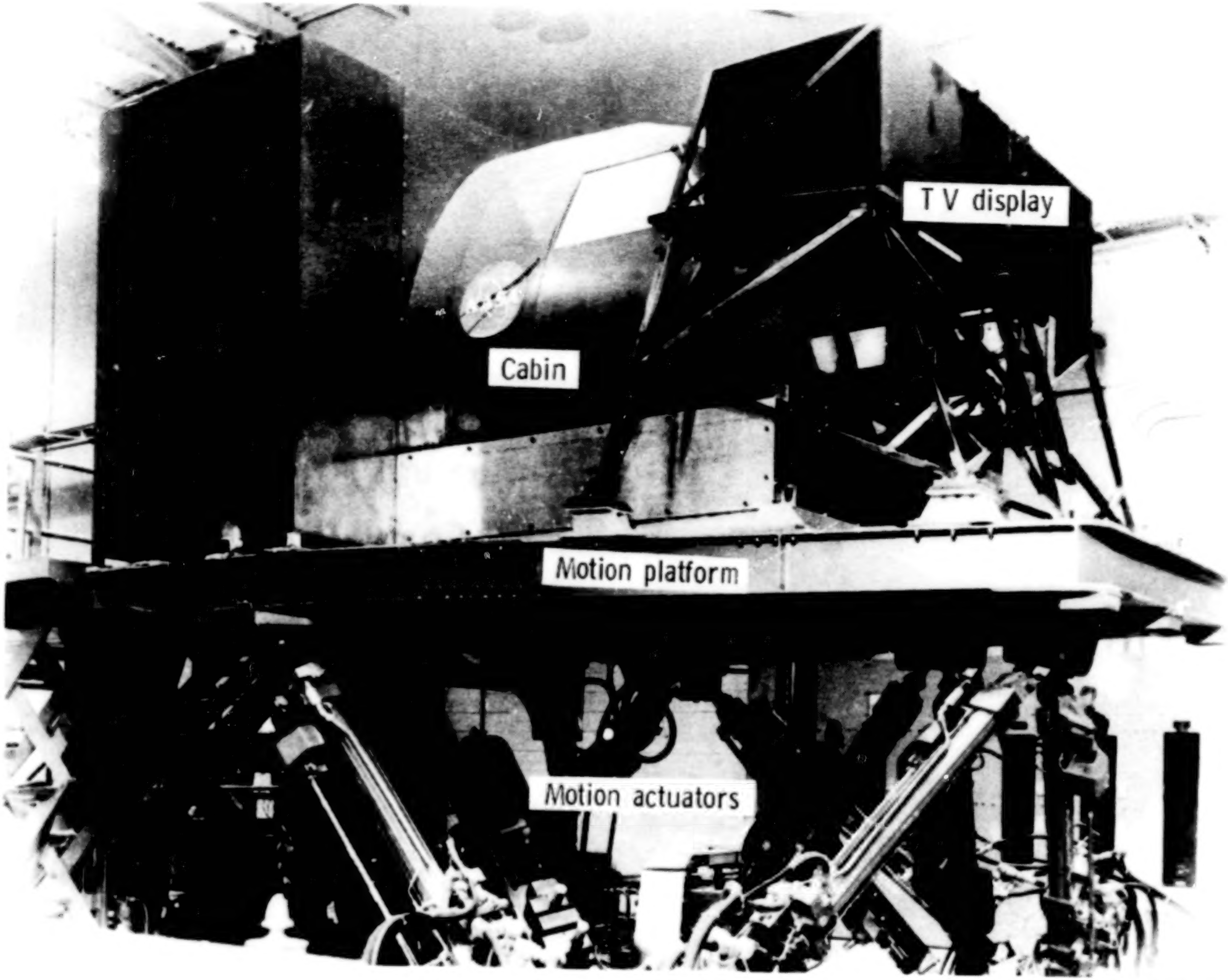
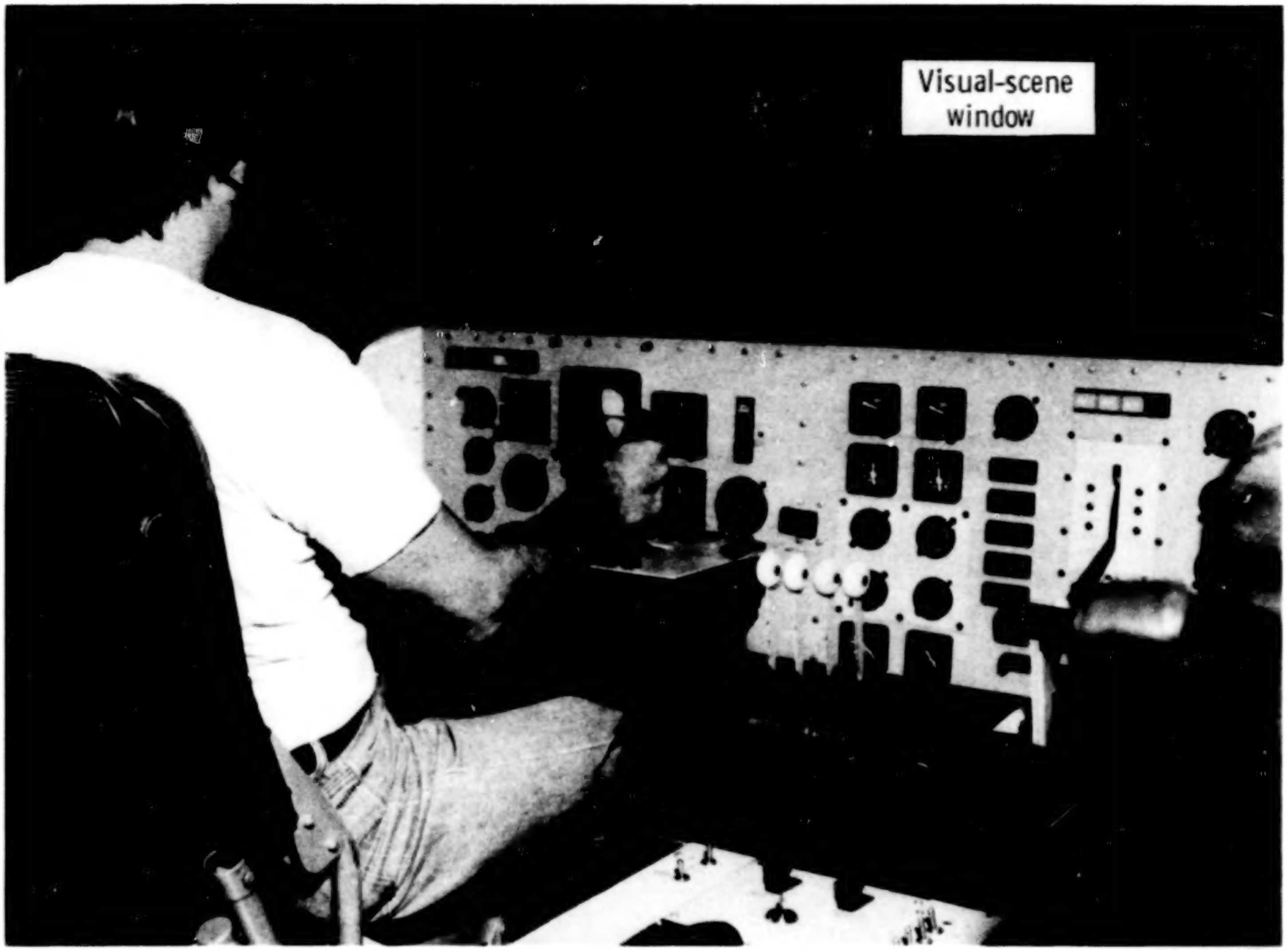


Figure 1.- System of body axes used. Positive directions are indicated.



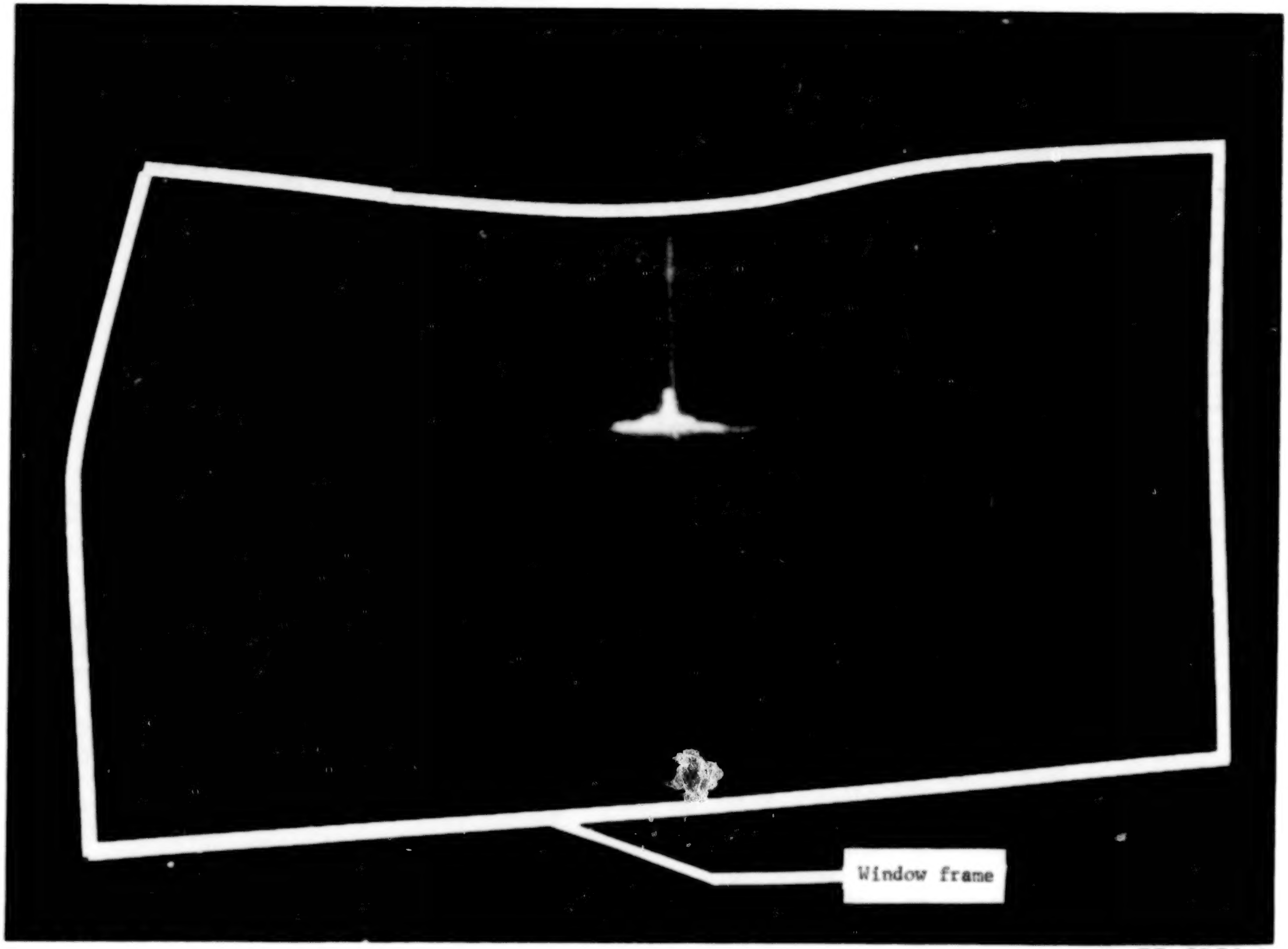
L-73-7163.1

Figure 2.- Langley six-degree-of-freedom vision-motion simulator.



L-78-7800.1

Figure 3.- Cockpit interior showing two-axis hand controller. Instruments and throttles were not activated for tests.



L-75-3154.1

Figure 4.- Photograph of visual scene observed by subjects when the simulated orbiter was nearly alined with the target aircraft. Target range was 182.88 m (600 ft).

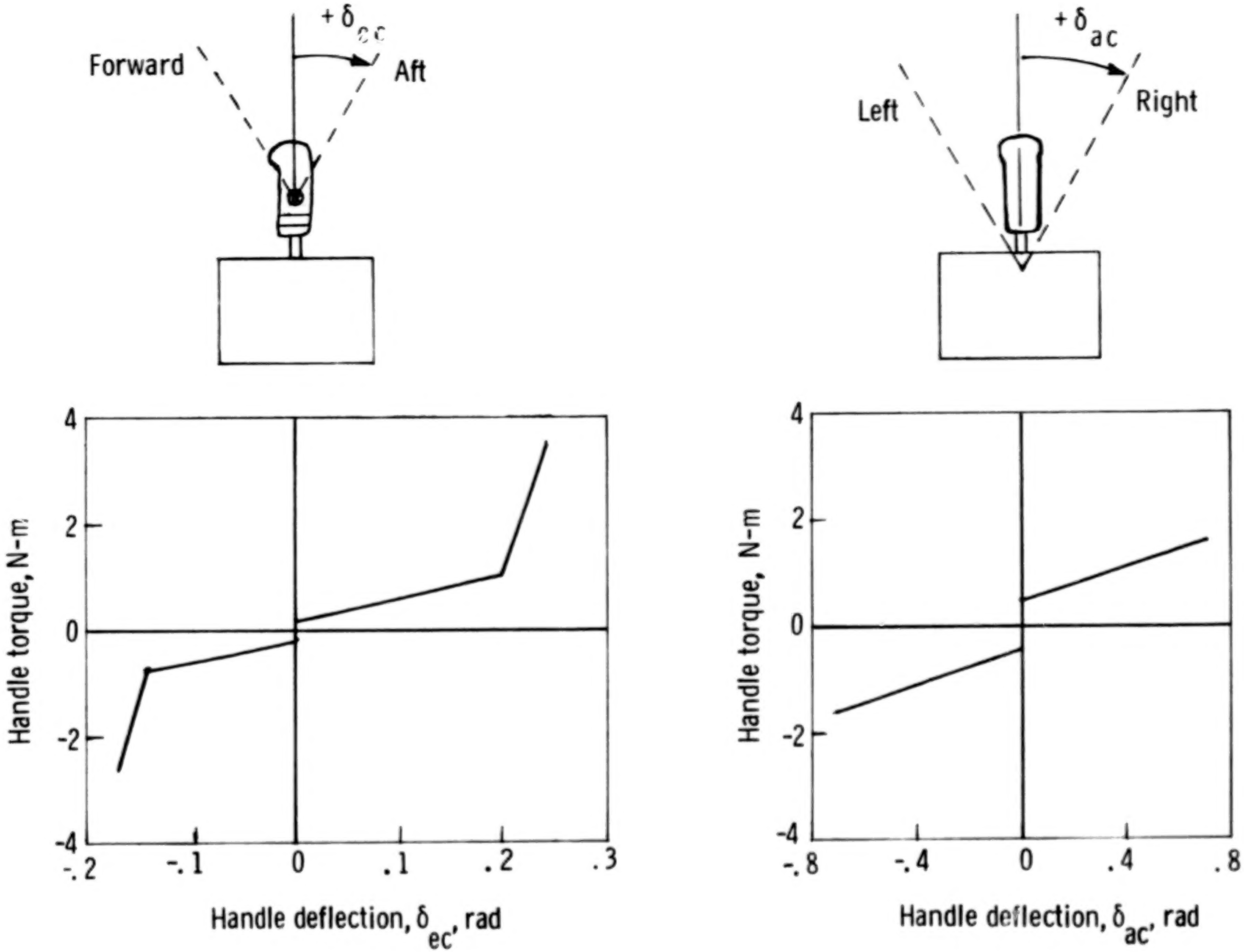
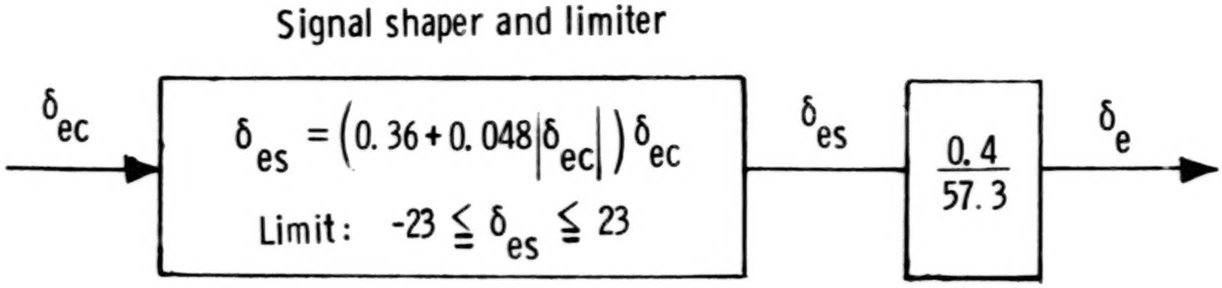
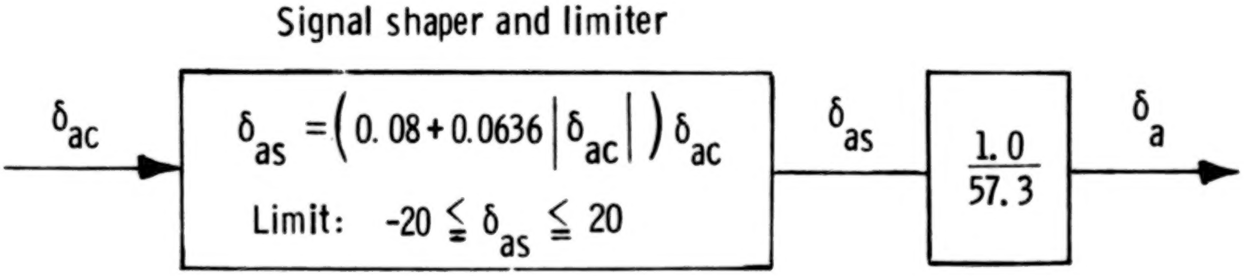


Figure 5.- Two-axis hand-controller torque-deflection characteristics.





Definitions

δ_{ec} hand-controller deflection in pitch (positive rearward), deg

δ_{ac} hand-controller deflection in roll(positive to right), deg

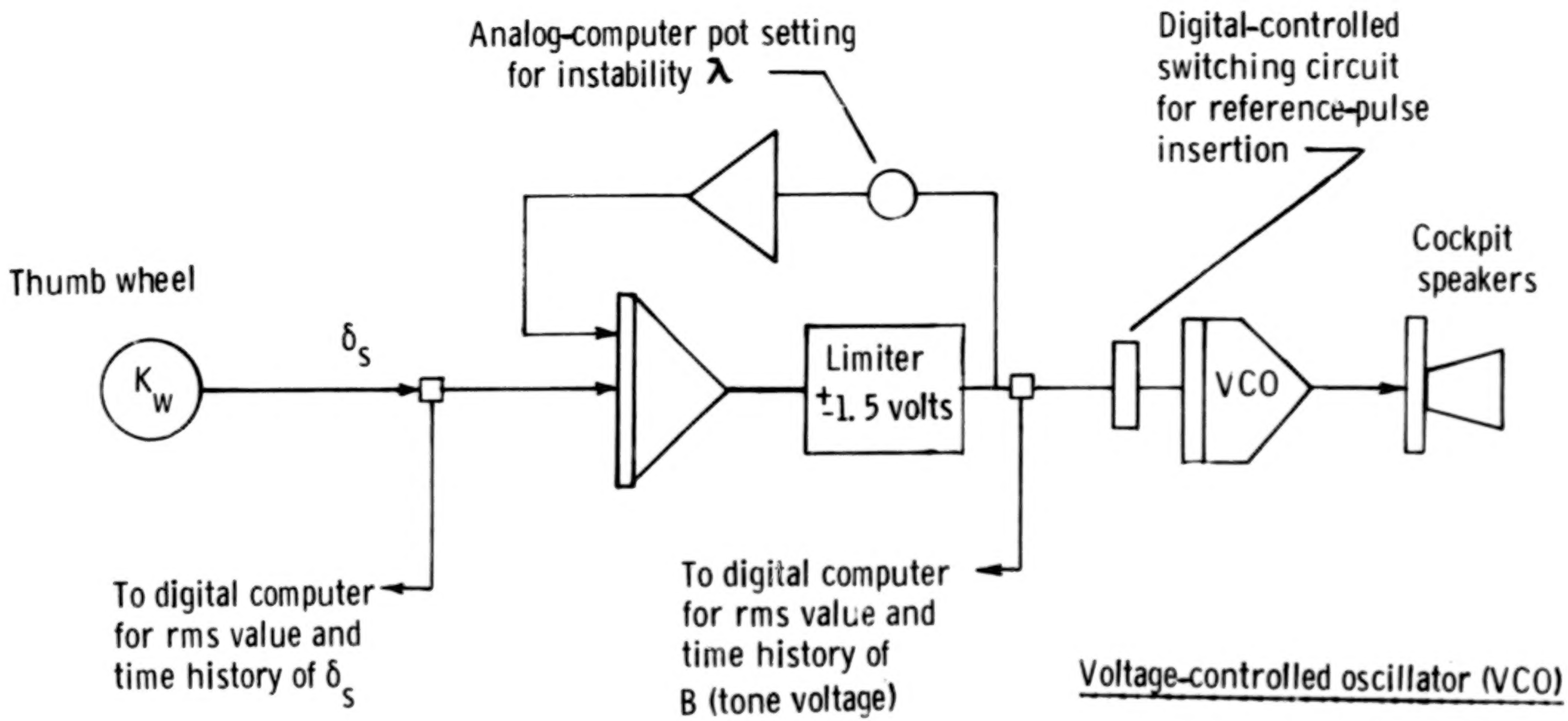
δ_{es} controller input in pitch after shaping and limiting, deg

δ_{as} controller input in roll after shaping and limiting, deg

δ_e pitch input after shaping, limiting, and scaling, rad

δ_a roll input after shaping, limiting,and scaling, rad

Figure 6.- Quadratic shaping, limiting, and scaling of hand-controller signal.



K_w = 0.0435 volts/deg thumb-wheel displacement

K_{VCO} = 466.67 Hz/volt

Figure 7.- Rudimentary sketch of audio side task.

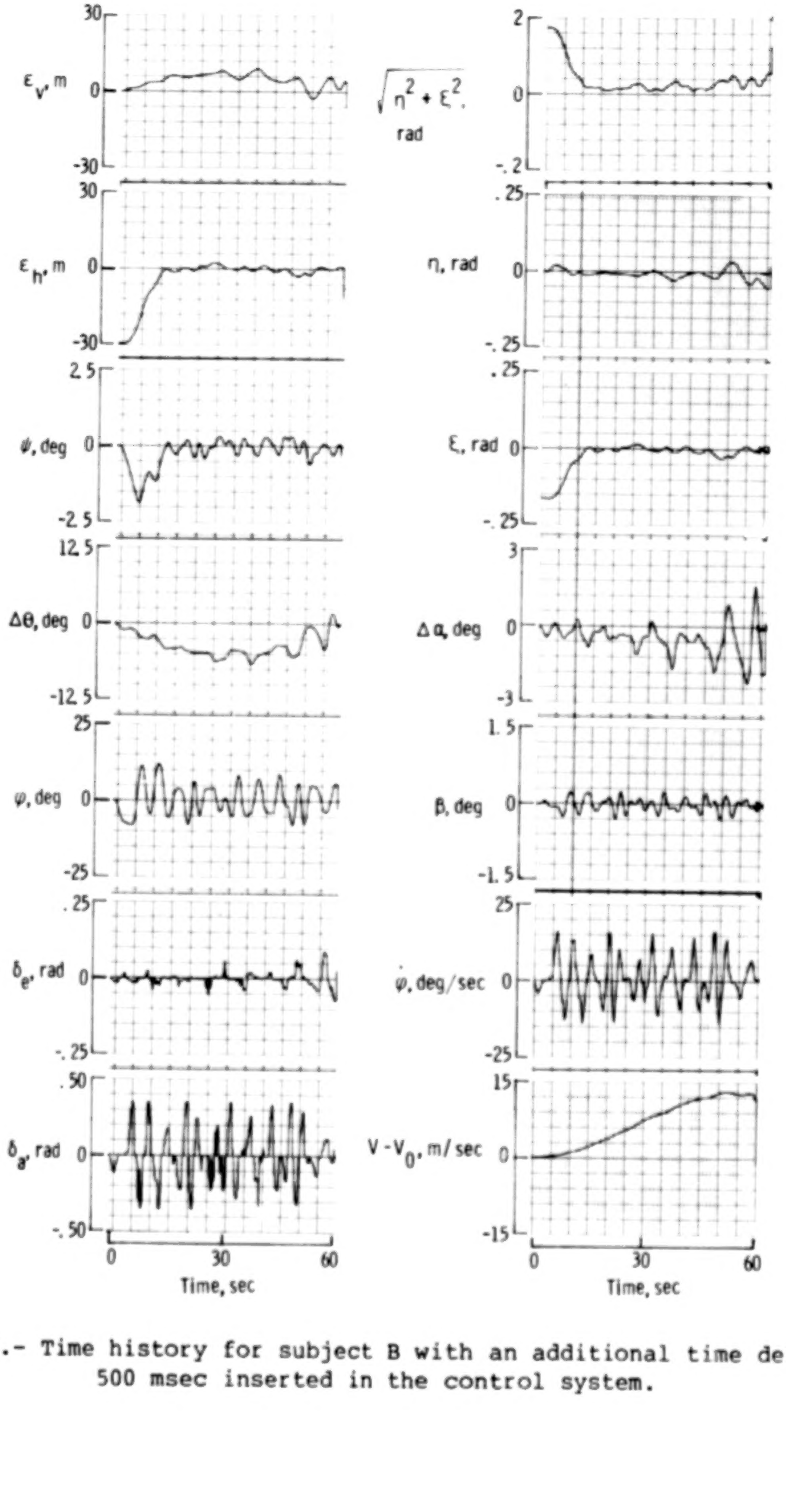
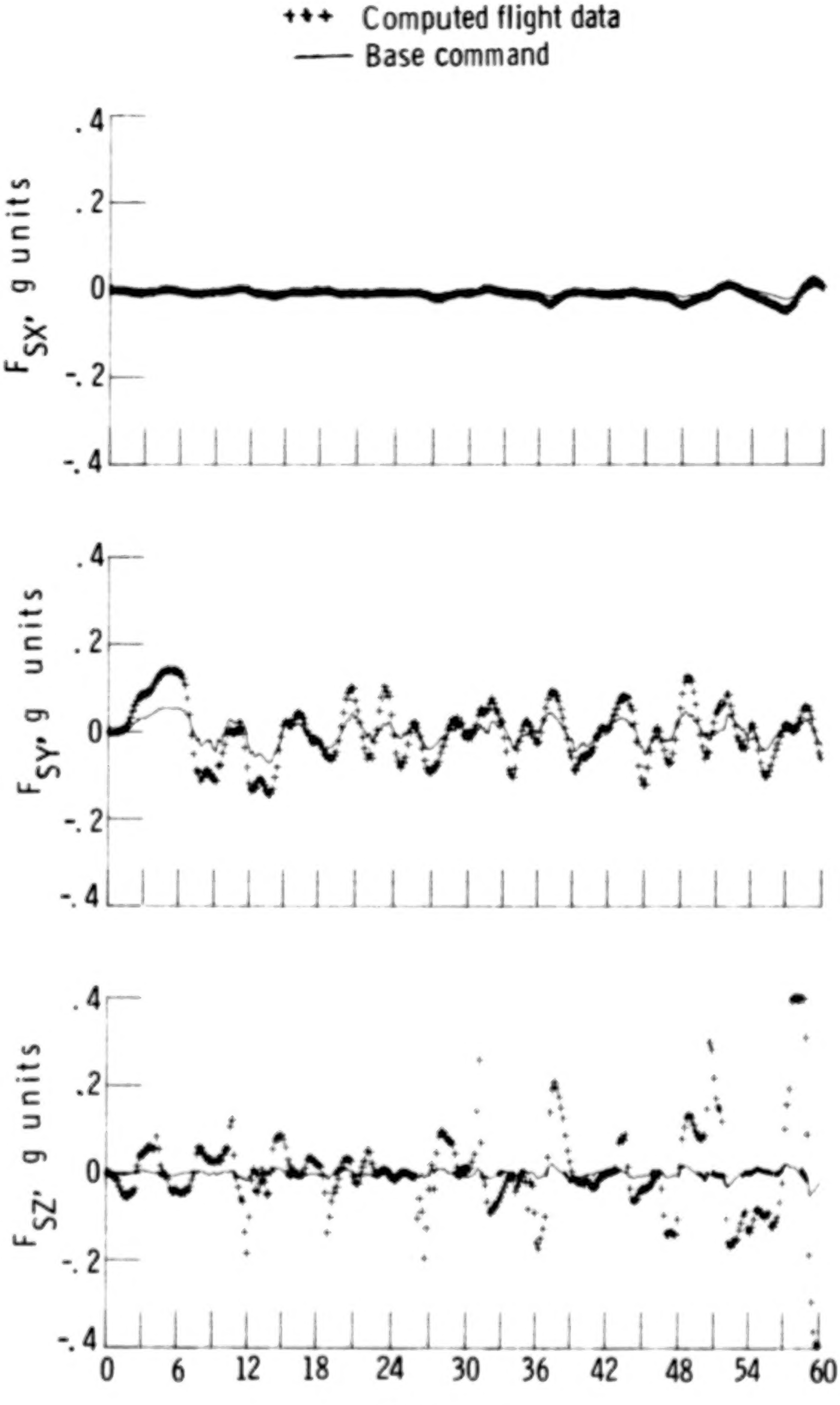
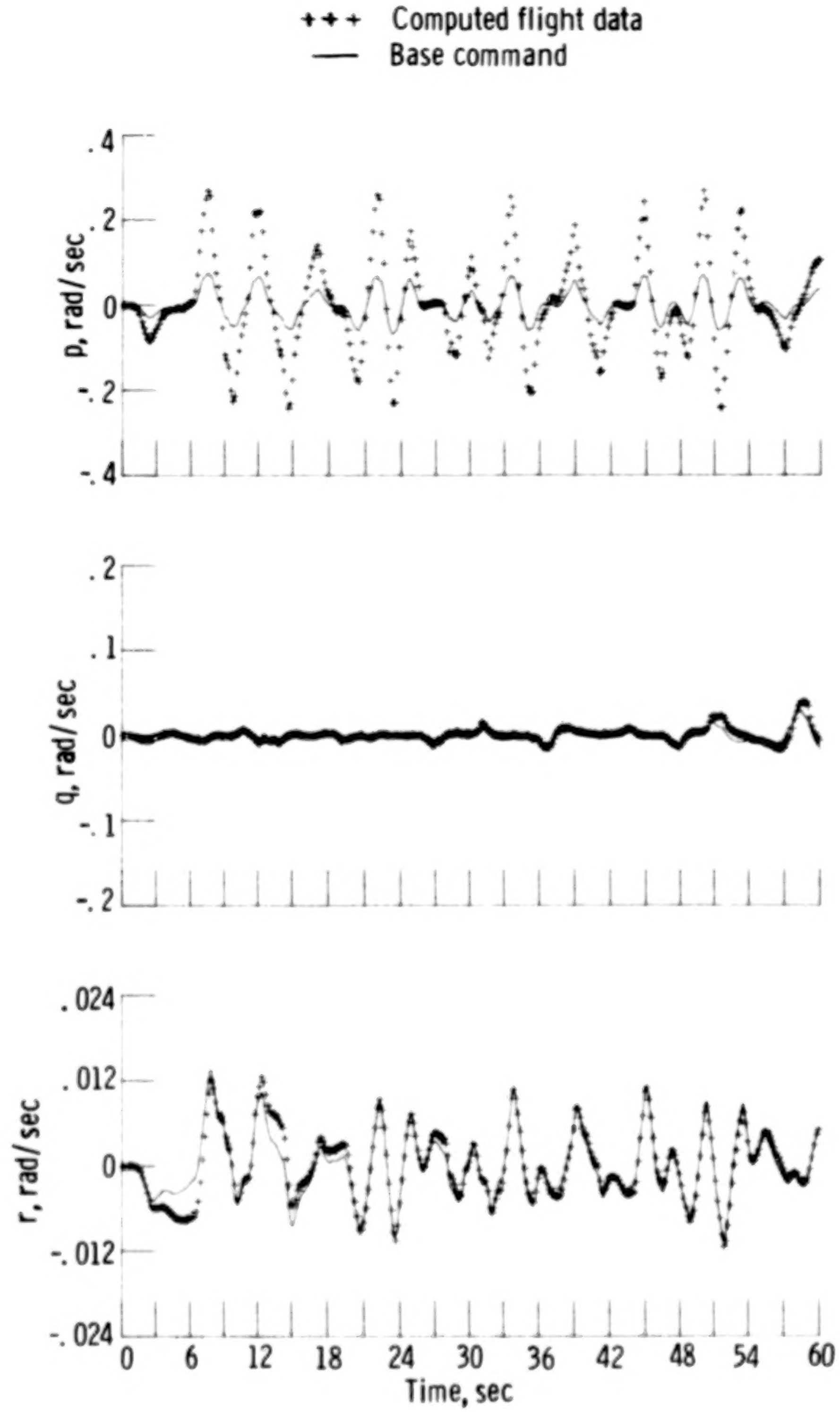


Figure 8.- Time history for subject B with an additional time delay of 500 msec inserted in the control system.



(a) Linear accelerations.

Figure 9.- Comparison of base commands with computed flight data for time history of figure 8. Subject B; 500 msec of added time delay.



(b) Angular rates.

Figure 9.- Concluded.

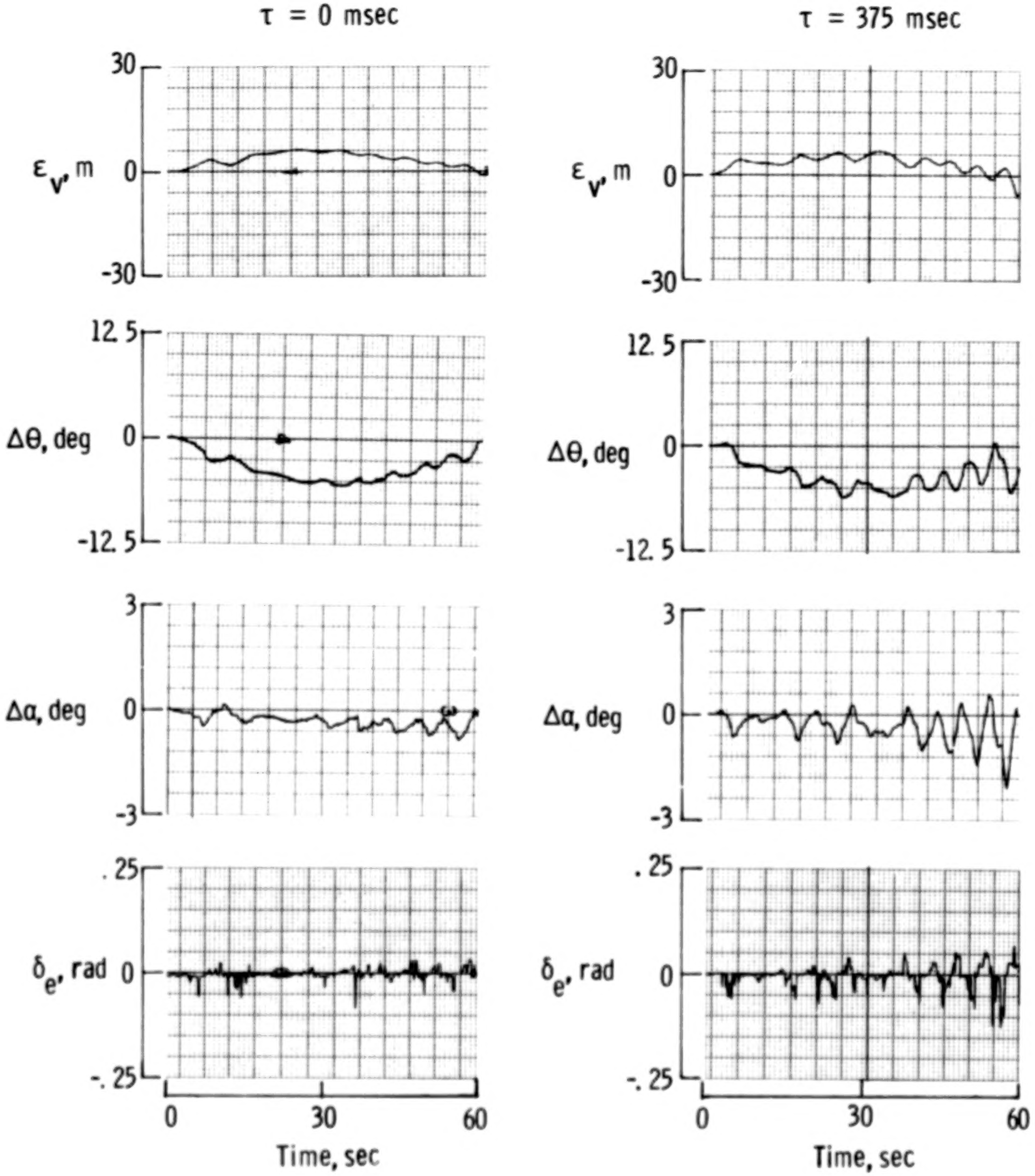
PIO OCCURRENCE

Upper value denotes number of runs PIO's encountered

Lower value denotes total number runs made

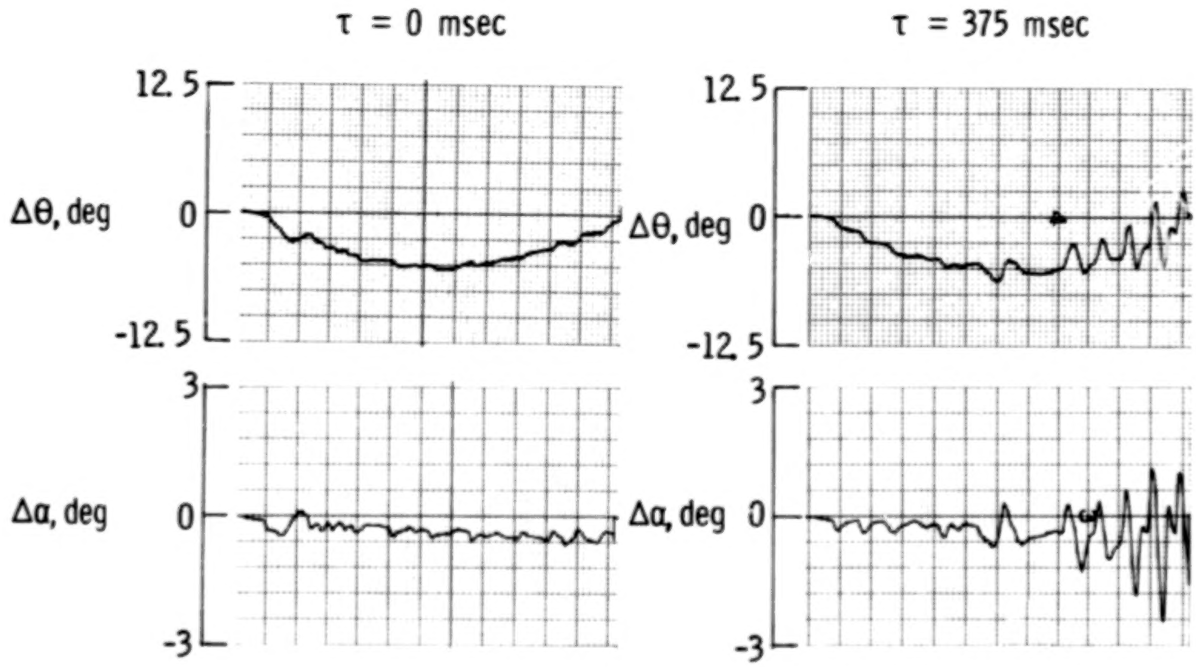
Test condition	Subject	Added time delay, msec					
		0	125	250	375	500	625
No side task	A	0/6	0/6	0/6	3/6	2/6	4/6
	B	0/6	0/6	1/6	5/6	6/6	---
	C	0/6	0/6	2/6	4/6	6/6	---
	D	0/6	0/6	2/6	4/6	1/6	3/6
	E	0/6	0/6	0/6	1/6	3/6	3/6
With side task	A	0/6	0/6	2/6	2/6	5/6	6/6
	B	0/6	0/6	3/6	6/6	6/6	---
	C	---	---	---	---	---	---
	D	---	---	---	---	---	---
	E	0/6	0/6	0/6	0/6	3/6	5/6

Figure 10.- Chart itemizing number of PIO occurrences for each test subject and added time delay.

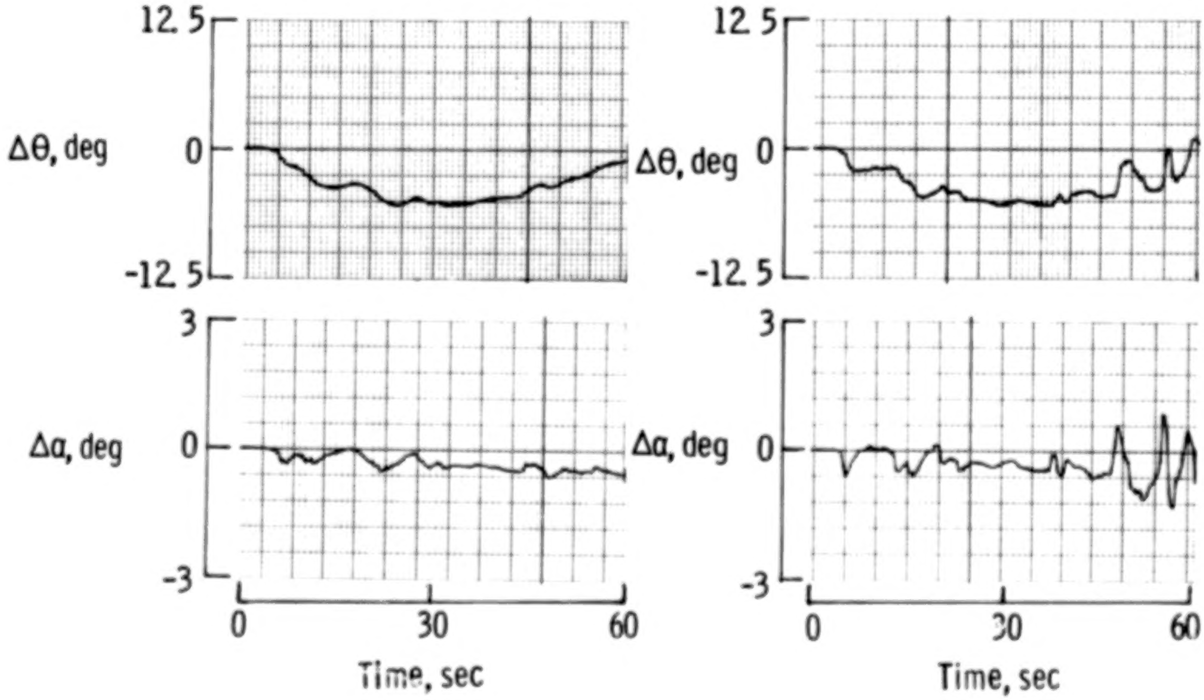


(a) Subject C.

Figure 11.- Typical time-history traces for three subjects indicating a longitudinal PIO occurs near the end of the run for the case of τ = 375 msec.

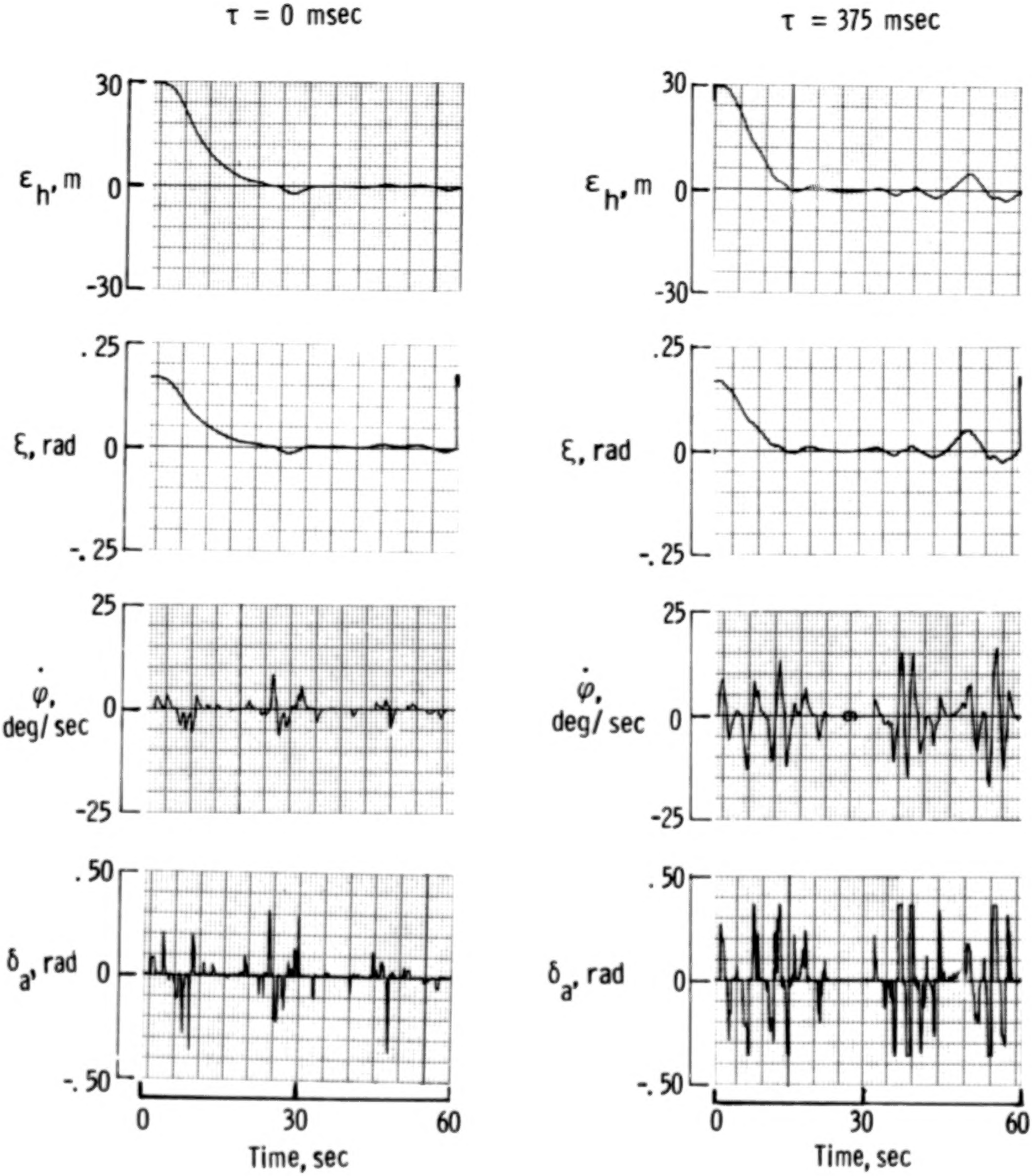


(b) Subject B.



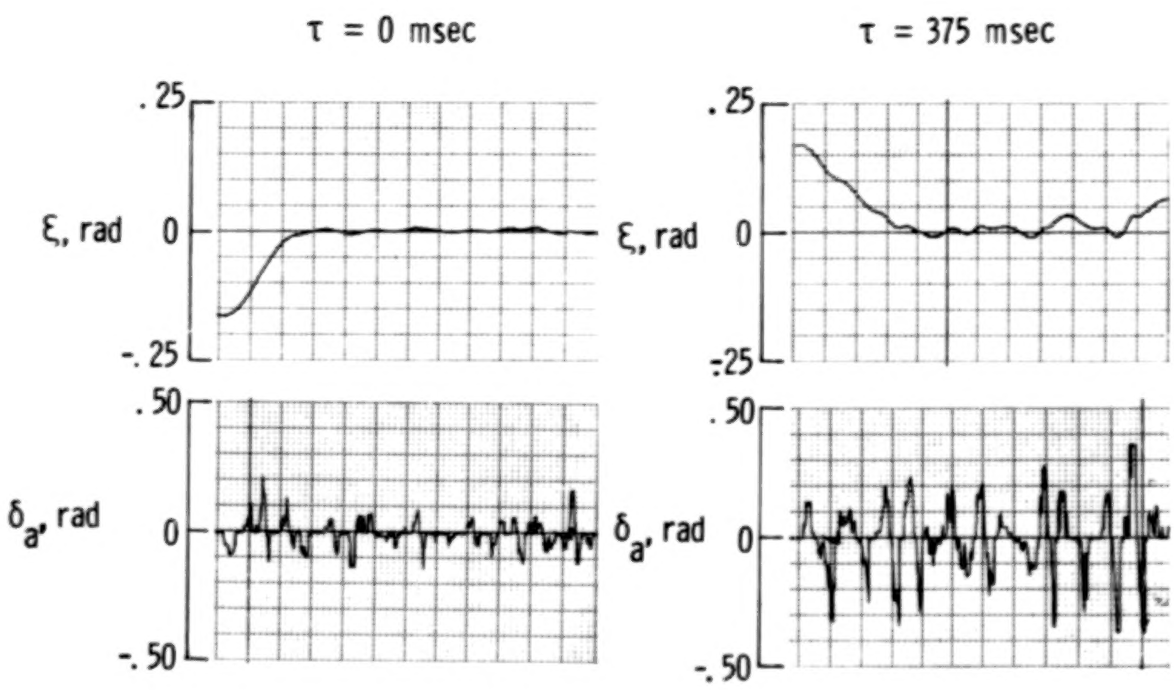
(c) Subject D.

Figure 11.- Concluded.

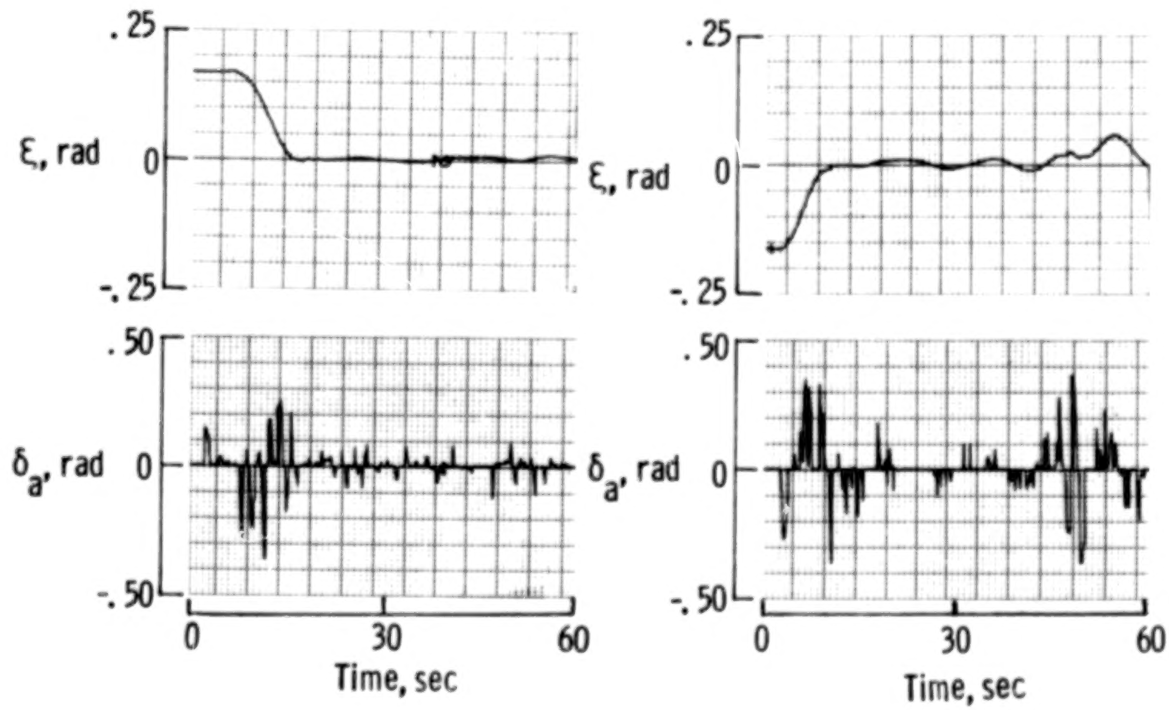


(a) Subject C.

Figure 12.- Typical time-history traces for three subjects indicating lateral PIO's for the case of τ = 375 msec.

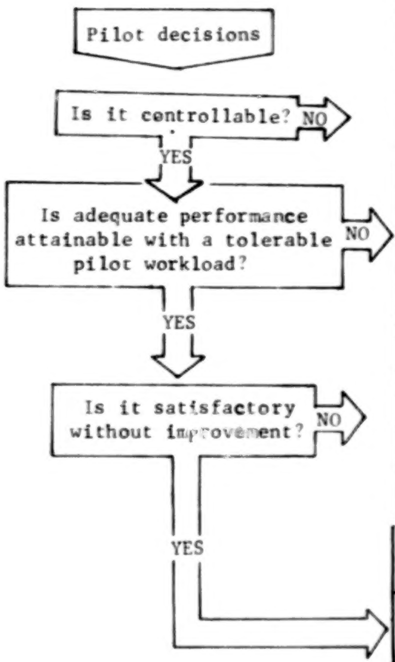


(b) Subject B.



(c) Subject D.

Figure 12.- Concluded.



ADEQUACY FOR SELECTED TASK OR OPERATION	AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION	PILOT RATING
Improvement mandatory	Major deficiencies	Control will be lost during some portion ot required operation	10
Deficiencies require improvement	Major deficiencies	Intense pilot compensation is required to retain control	9
	Major deficiencies	Considerable pilot compensation is required for control	8
	Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
Deficiencies warrant improvement	Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
	Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
	Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
	Fair - some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
	Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
	Excellent Highly desirable	Pilot compensation not a factor for desired performance	1

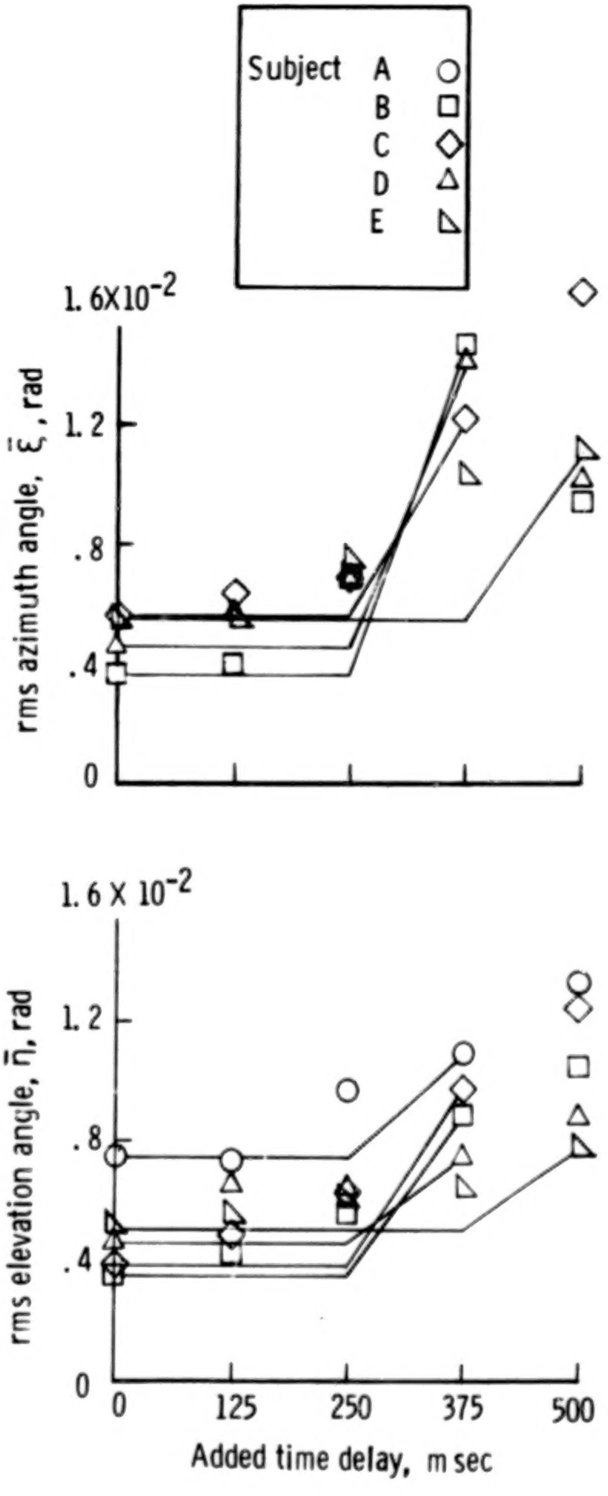
Figure 13.- Cooper-Harper rating scale.

PILOT RATINGS

Task	Subject	Added time delay, msec		
		0	250	500
No side task	A	3		6
	B	3	5	7
	C*	3, 4	5, 6	9, 8
	D	3	$4\frac{1}{2}$	6
With side task	A	5		8
	B	4	6	8
	C	---	---	---
	D	---	---	---

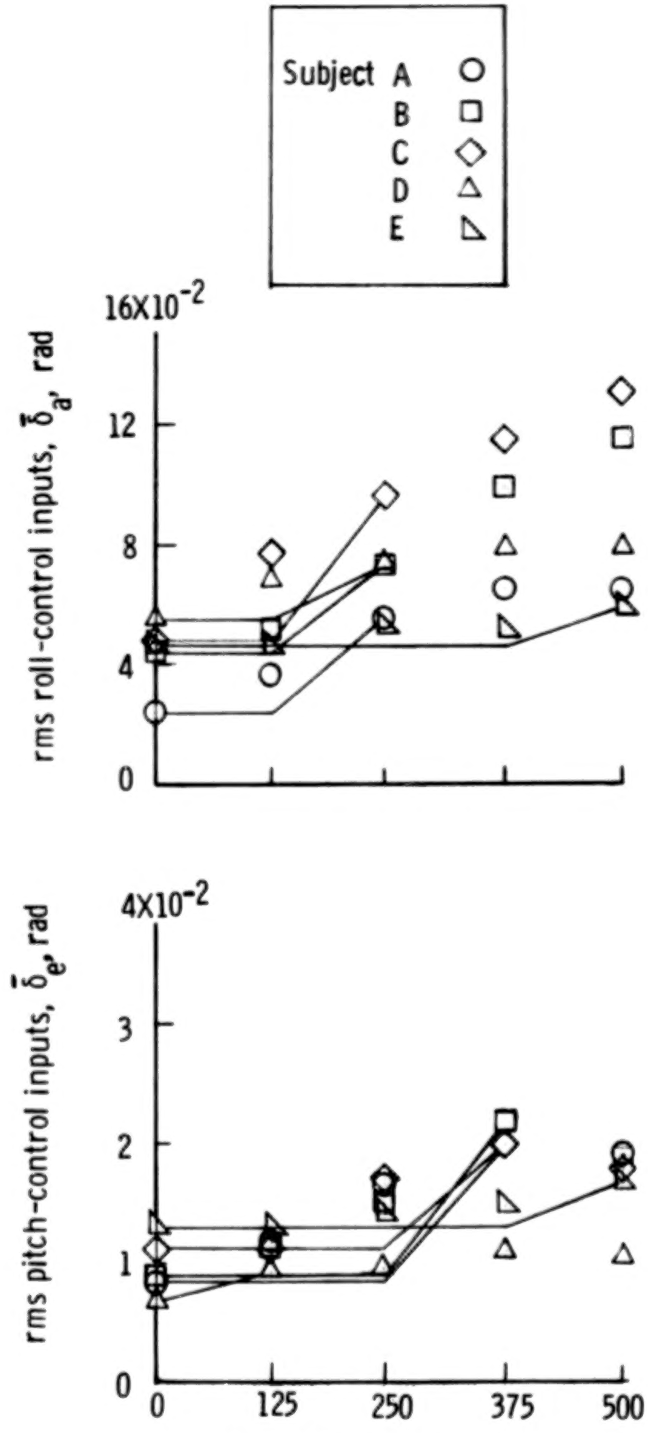
* The first value denotes longitudinal characteristics; the second value denotes lateral characteristics.

Figure 14.- Cooper-Harper ratings for vehicle handling qualities given by astronauts and research pilots. Subject C gave two values for each condition.



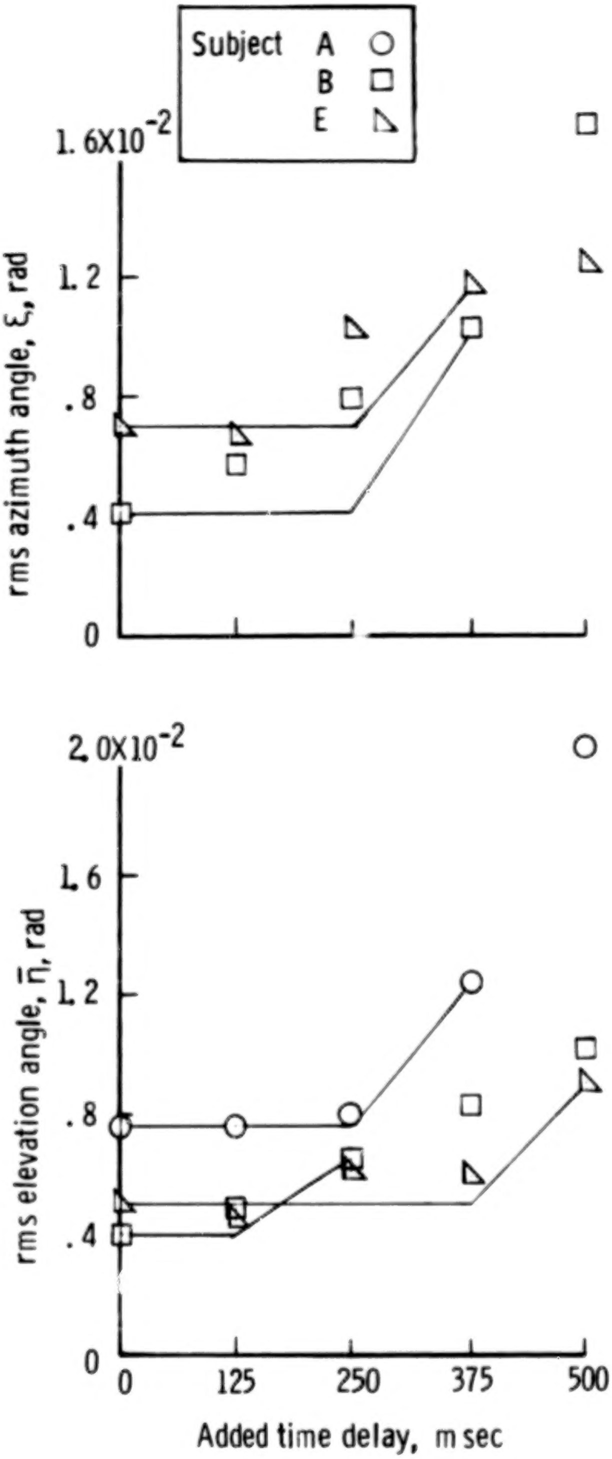
(a) Tracking errors.

Figure 15.- Pilot-performance measures with no side task. The azimuth-angle results are for the last 30 sec of the run.



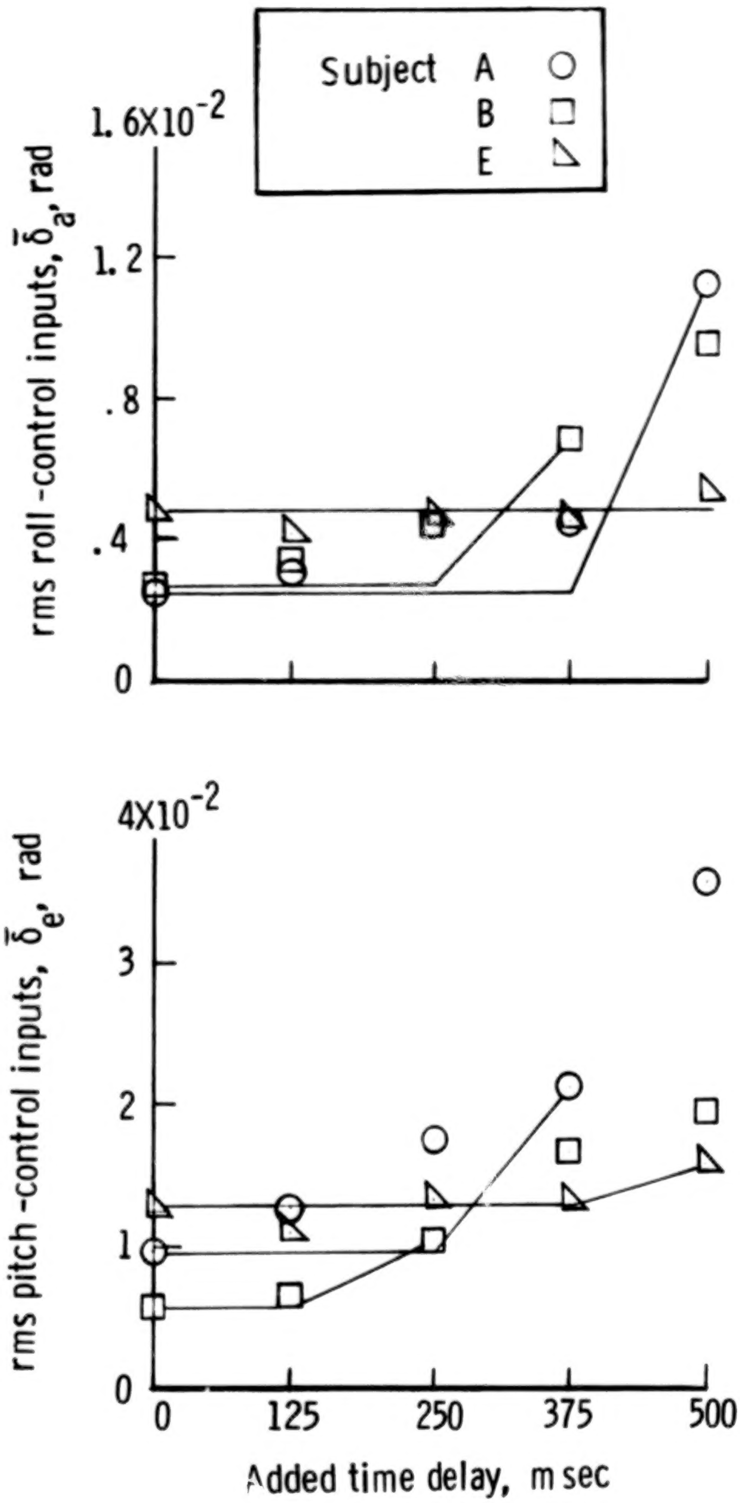
(b) Hand-controller inputs.

Figure 15.- Concluded.



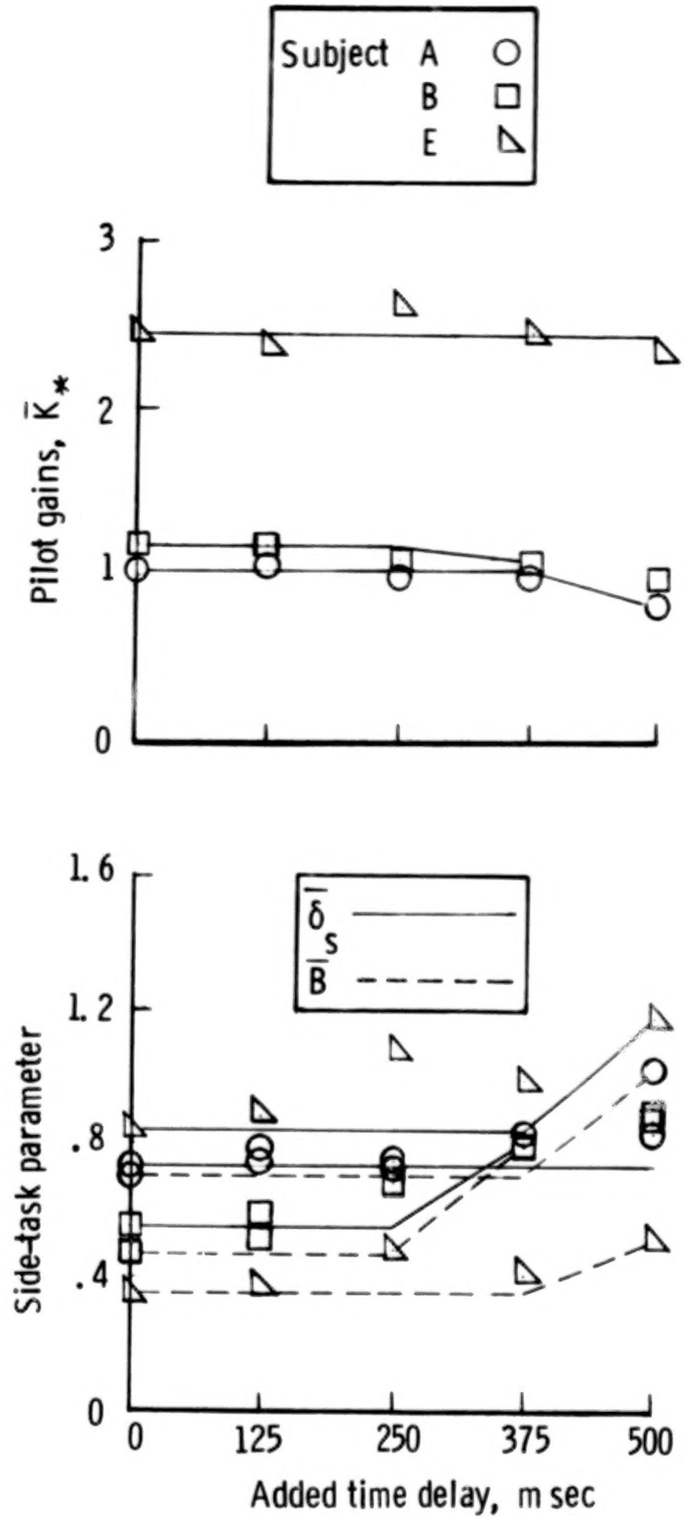
(a) Tracking errors.

Figure 16.- Pilot-performance measures with side task. The azimuth-angle results are for the last 30 sec of the run.



(b) Hand-controller inputs.

Figure 16.- Continued.



(c) Audio side-task measures.

Figure 16.- Concluded.

PIO OCCURRENCE

Upper value denotes number of runs PIO's encountered

Lower value denotes number of runs made

Test configuration	Added time delay, m sec					
	0	125	250	375	500	625
$\tau_r = \tau_p$	0/6	0/6	3/6	6/6	6/6	---
$\tau_r = 125$; τ_p varied	---	0/6	0/6	[a]2/6	[a]3/6	[a]4/6

[a]All pitch PIO's.

PILOT RATINGS

Test configuration	Added time delay, m sec				
	0	125	250	375	500
$\tau_p = \tau_p$	4		6		8
$\tau_r = 125$; τ_p varied	---	4	5		8

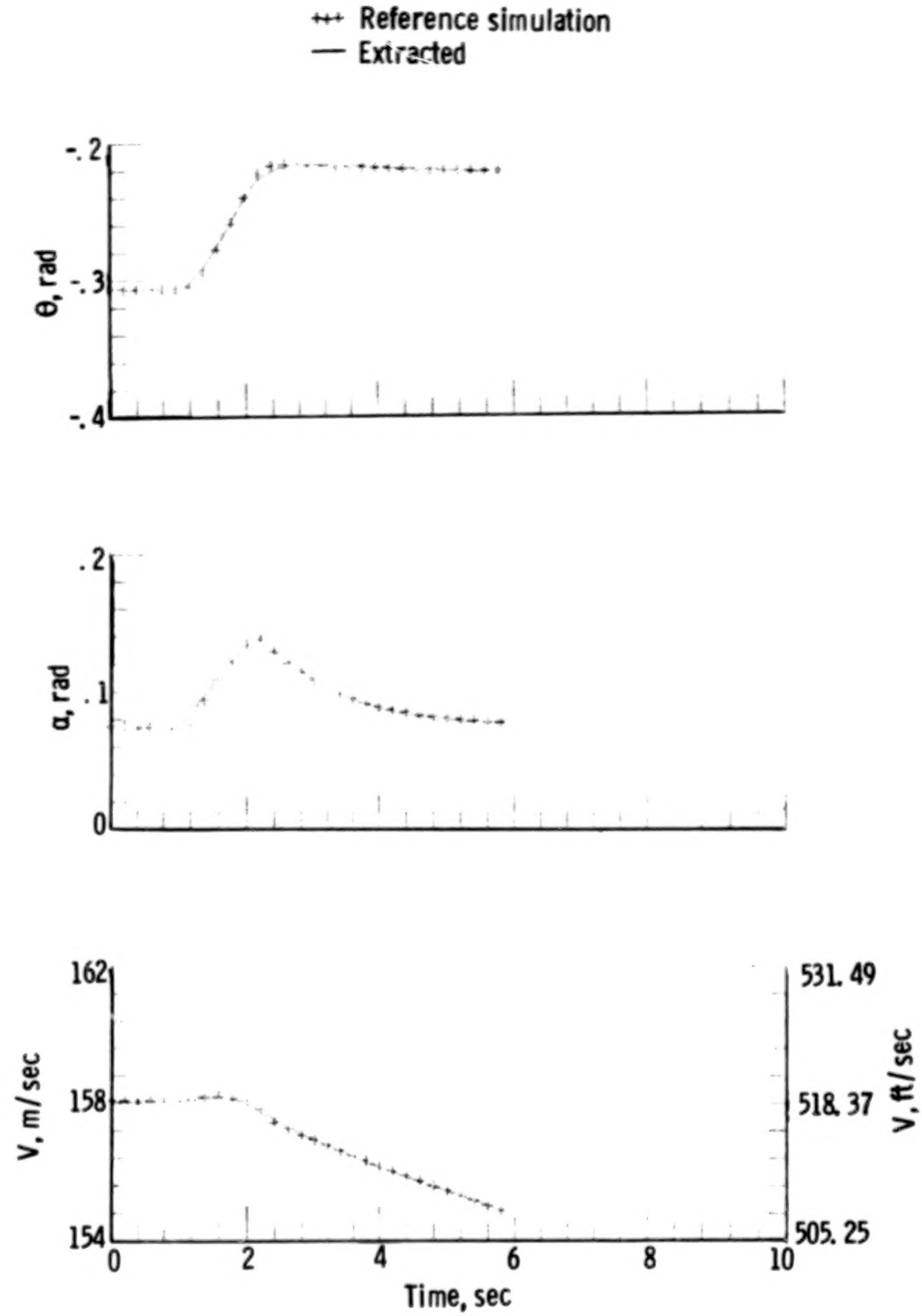
TRACKING PERFORMANCE

Earliest Breakpoint Location for Elevation and Azimuth Line-of-Sight Angles

Test configuration	Added time delay, m sec				
	0	125	250	375	500
$\tau_r = \tau_p$			(b)		
$\tau_r = 125$; τ_p varied				(b)	

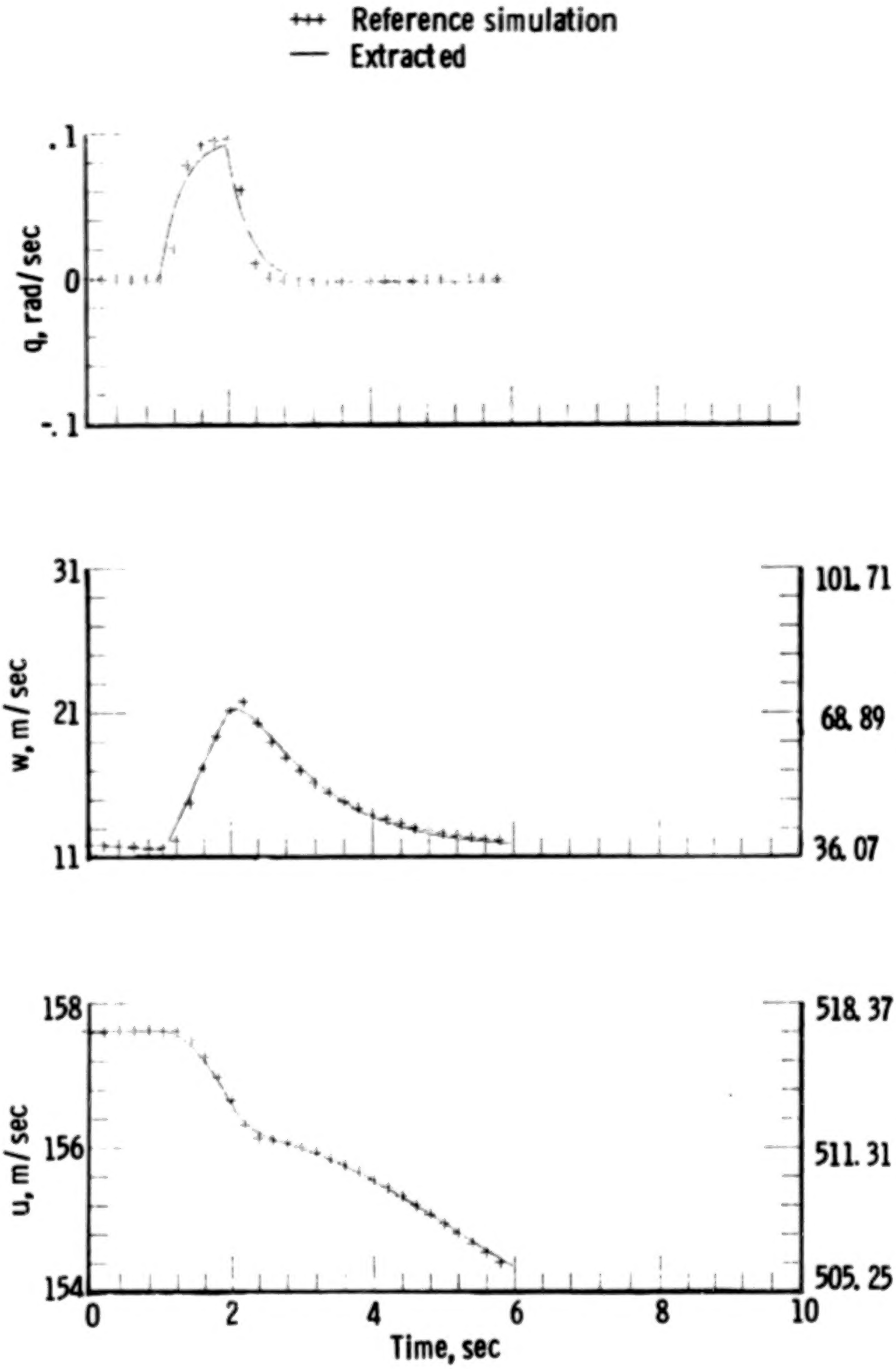
[b]Breakpoint.

Figure 17.- Mismatched delay data (τ_r held constant) compared with data for equal delays in both control channels. Results for subject B using the side task.



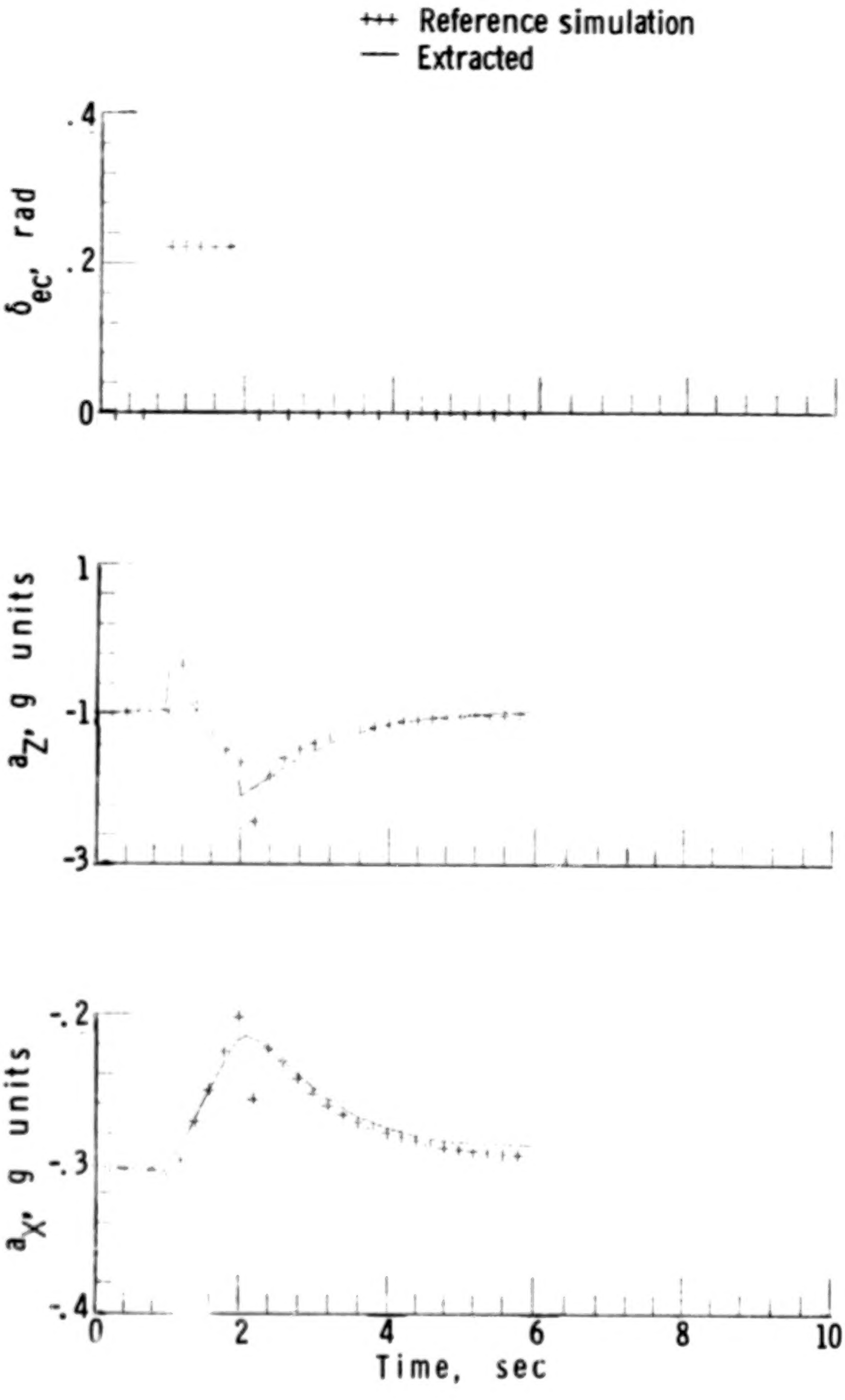
(a) Angles and total speed.

Figure 18.- Time-history comparisons of motions computed by using extracted derivatives with those of the reference simulation. Longitudinal case for 1-sec pitch-pulse input inserted at $t = 1$ sec.



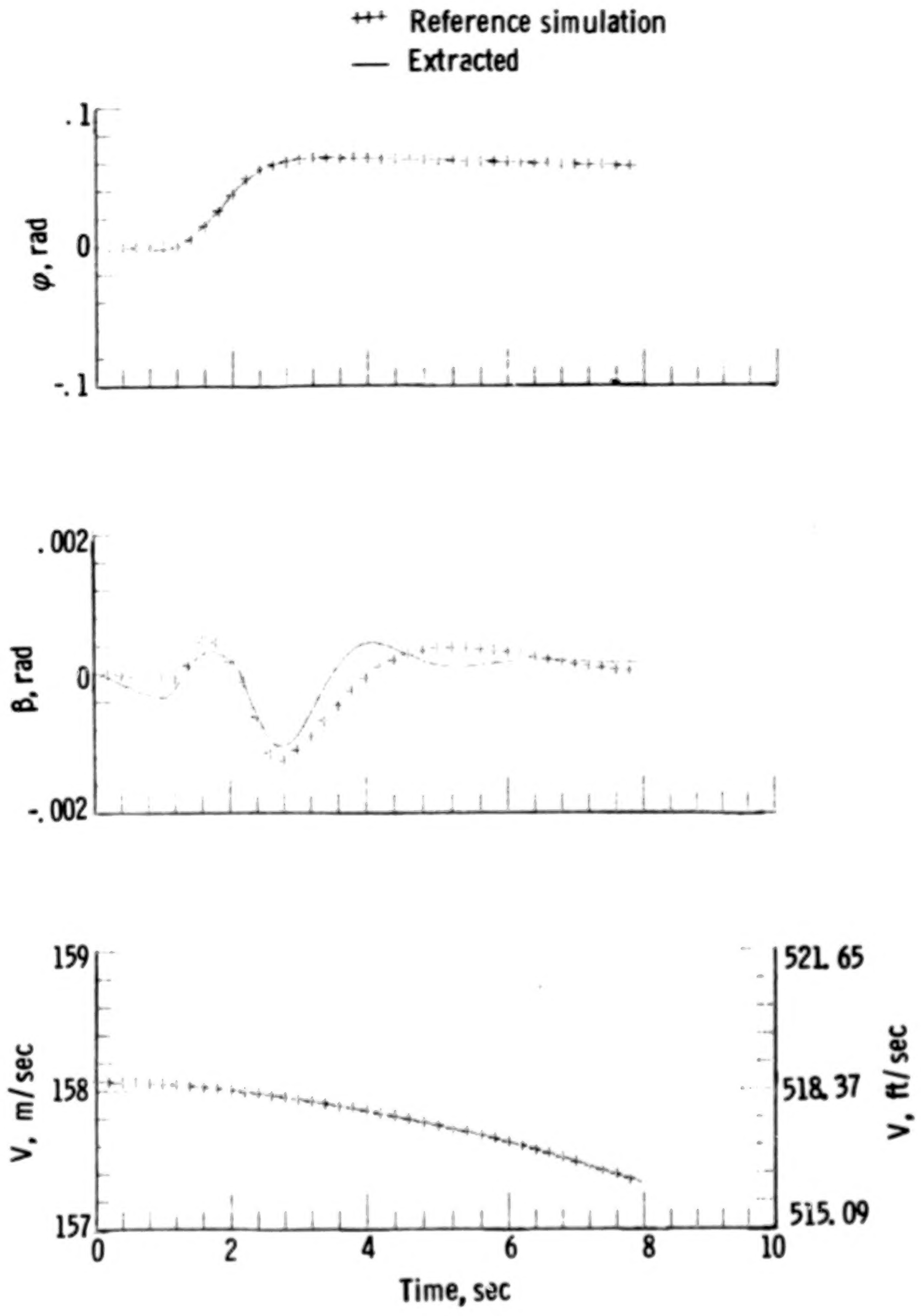
(b) Velocity components and pitch rate.

Figure 18.- Continued.



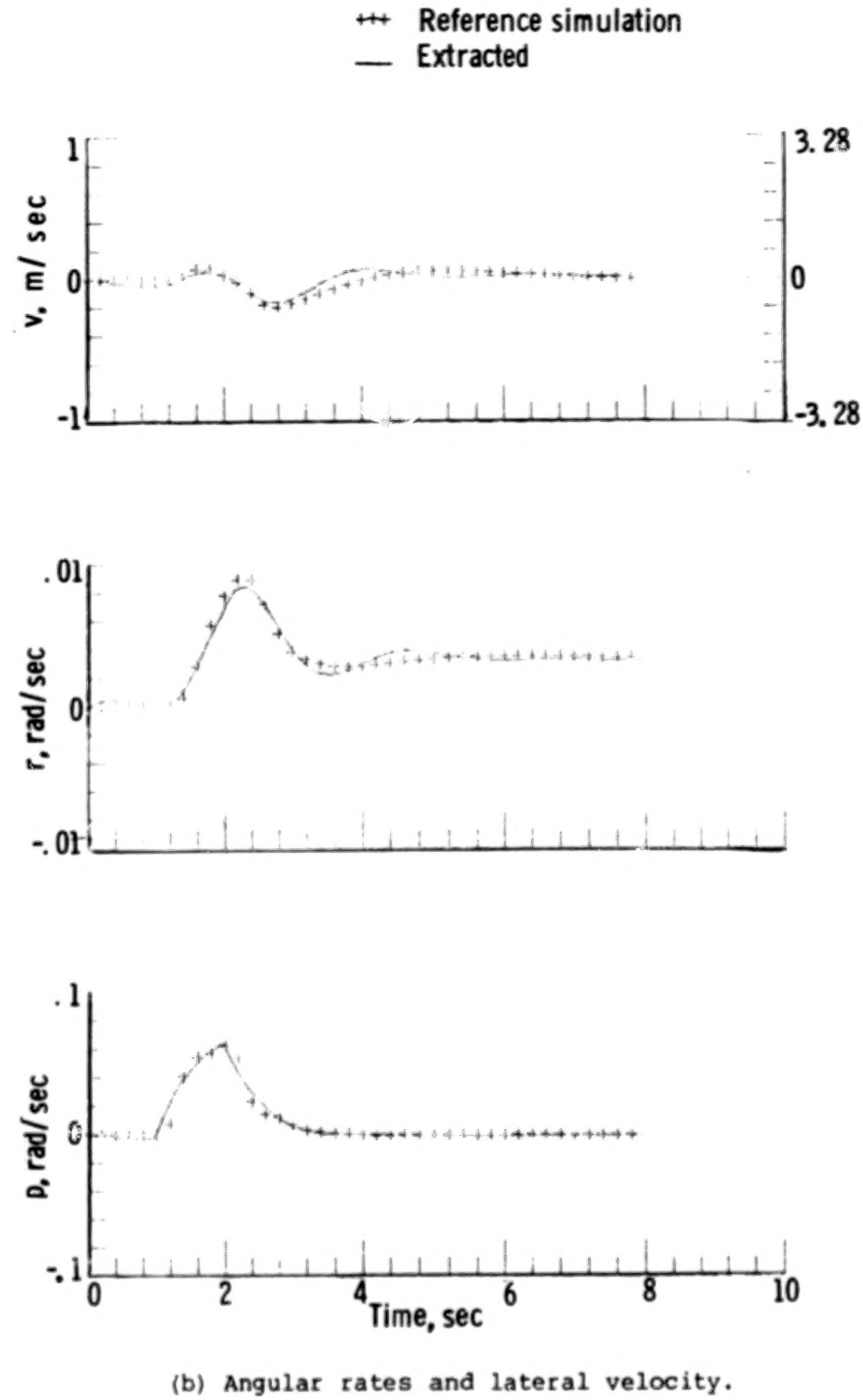
(c) Accelerations and controller input.

Figure 18.- Concluded.



(a) Angles and total speed.

Figure 19.- Time-history comparisons of motions computed by using extracted derivatives with those of the reference simulation. Lateral case for 1-sec roll-pulse input inserted at $t = 1$ sec.



(b) Angular rates and lateral velocity.

Figure 19.- Continued.

SIMULATOR STUDY OF THE EFFECT OF CONTROL-SYSTEM TIME
DELAYS ON THE OCCURRENCE OF PILOT-INDUCED OSCILLATIONS
AND ON PILOT TRACKING PERFORMANCE... NASA TECH.PAPER
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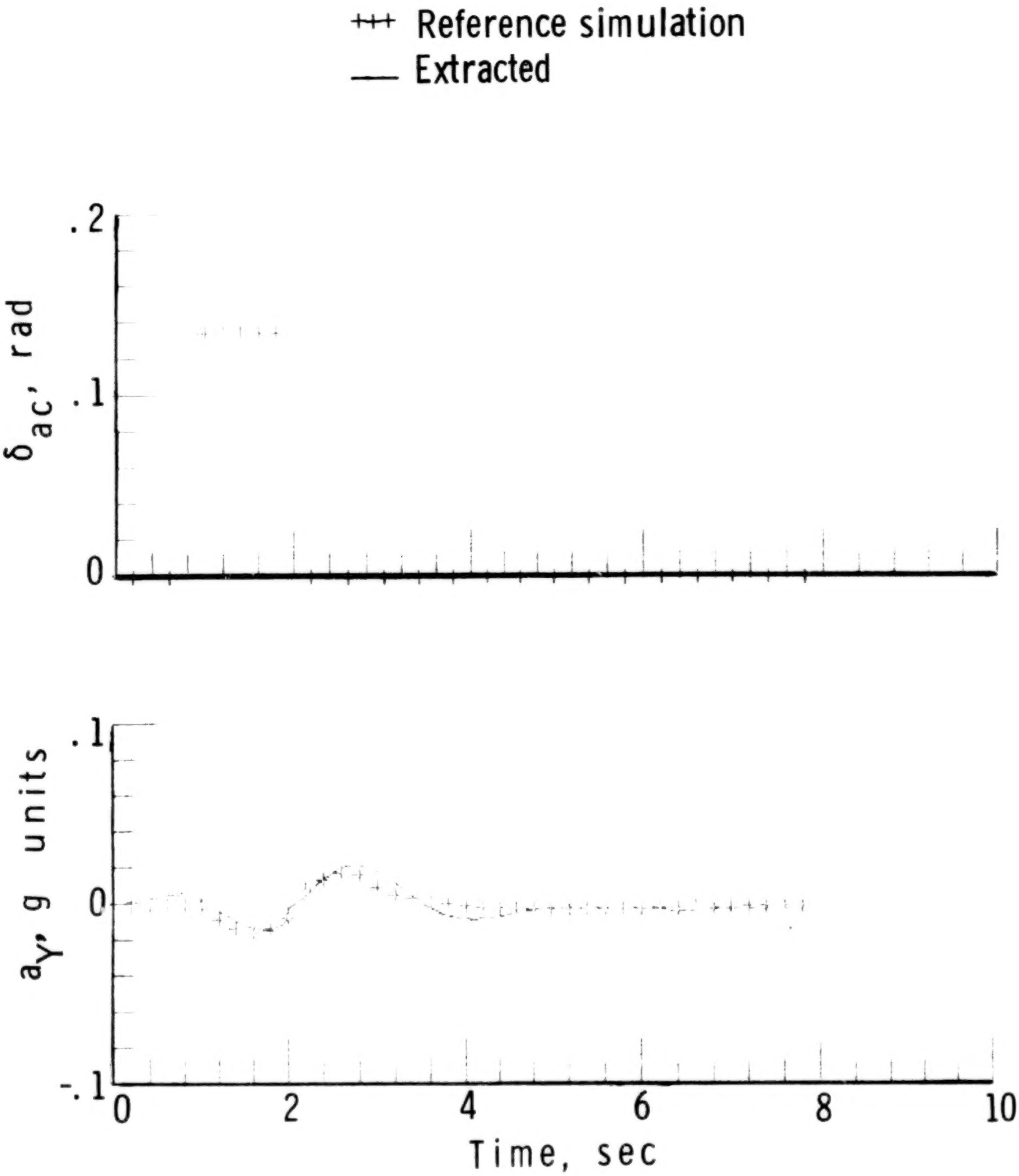

(c) Acceleration and control input.

Figure 19.- Concluded.

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15. Supplementary Notes

16. Abstract

An experimental study using a six-degree-of-freedom motion-base simulator has been made to determine the effect of control-system time delays on the occurrence of pilot-induced oscillations (PIO's) on the vehicle handling qualities and on pilot tracking performance for a landing-approach configuration of the Space-Shuttle orbiter. A linearized math model was employed which represented a 300-knot orbiter with almost all time delays removed. Additional time delays were then inserted following the pilot's hand-controller signals. Only pitch and roll commands were used for vehicle control. The simulation employed an air-to-air tracking task as a means of emphasizing PIO tendencies. Two astronauts, two research pilots, and one simulation engineer served as test subjects. Results showed that PIO's occurred when the amount of added time delay approximated that existing for the orbiter configuration flown in the approach and landing tests (ALT). Increasing the amount of delay increased PIO occurrences and resulted in degraded tracking performance. Decreasing the amount of time delay eliminated the PIO's.

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